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PATH SELECTION SYSTEM DEVELOPMENT AND EVALUATION FOR A MARTIAN ROVING VEHICLE

by

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Analysis and Design of a Capsule Landing System and Surface Vehicle Control System for Mars Exploration

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ABSTRACT

A path selection system evaluation test procedure has been developed to enhance the analysis capability of an existing digital computer simulation package. The procedure investigates the obstacle avoidance ability of a path selection system on a sequence of test terrains with and without random effects.

Using the standard test procedure a proposed mid-range sensor system has been evaluated and recommendations directed at improving the performance of the system have been made. In addition, the initial development and evaluation of a short range sensor system has been undertaken.

I. INTRODUCTION

The development of an autonomous vehicular path selection control system is mandatory for the success of an unmanned Mars exploration mission. Due to the large communication delay time (from nine to twenty-five minutes) between Martian and Earth control stations this system must operate with a high degree of reliability. The system should be able to select a path to a specified destination such that dangerous obstacles are avoided and other mission considerations are met.

Previous efforts concerning this area of investigation have concentrated upon the development of a comprehensive digital computer simulation package for the purpose of evaluating proposed path selection systems and developing new path selection system concepts. A description of the development of this simulation program may be found in Ref. 1. The computer package has the capability of simulating a wide range of path selection systems over a variety of terrain characteristics. To enhance the realism of the program, a number of non-ideal features were incorporated. These include: vehicle bounce, sensor-reading error, and slope measurement error (see Section II-A). In addition, the program has the capability of quantitatively evaluating system performance using established criteria.

The subject of this report is three-fold. The first subject discussed is the development of standard test terrains and simulation procedure. The purpose of this activity is to facilitate the use of the simulation program as an evaluation tool. Next, using the standard test terrains, a proposed mid-range sensor system has been evaluated. As a result of the evaluation a number of recommendations directed at improving the system have been proposed and will be investigated in future work. Finally, the initial development and evaluation of a short range sensor system has been undertaken. The objective of this activity was to determine if successful navigation could be effectively performed given a sensor with a maximum range capability of three meters.

The following section presents a discussion of the standard test terrains and simulation procedure. The evaluation of the proposed mid-range sensor system is discussed in Section III. Section IV contains a discussion of the initial development and evaluation of the short range sensor system. The final section presents a summary of progress and suggestions for future work.

II. DEVELOPMENT OF STANDARD TEST TERRAINS AND EVALUATION PROCEDURE

To facilitate the use of the computer simulation package as an evaluation tool, the development of a standard testing procedure has been undertaken. This testing procedure consists of investigating the obstacle avoidance behavior of a path selection system by simulating the system's performance on a sequence of test terrains in the presence of random effects.

In developing this testing sequence an effort was made to determine general rules for the structuring of test terrains, the use of random effects, and the examination of system characteristics that would provide the most information from each simulation. The developed testing sequence will not only provide the program user with a set of terrains and techniques to meet his analysis needs but also a set of guidelines for incorporating additional test situations into the sequence as the need arises.

A. The Use of Random Effects

The simulation package has the capability of adding uniformly distributed white noise to a variety of variables in a given simulation. The program user specifies the mean and maximum deviation of the noise and the variable to which it is to be added. If desired, the noise can be filtered before the addition. If the noise is filtered a second order filter is used and the program user specifies the filter's damping ratio and natural frequency.

The testing sequences employ this noise capability to simulate a path selection system's performance in the presence of the types of noise corruption found in a realistic environment. The use of attitude, range and slope measurement noise are discussed below.

1. Attitude Noise

Attitude noise is a term used for the random effects encountered during a range measurement due to the pitching and rolling motion of the vehicle as it passes over terrain irregularities. To create the effect of a rubble strewn test terrain, filtered white noise is added to the vehicle's in-path and cross-path slopes, thereby randomly tilting the vehicle and perturbing the sensor orientation accordingly. Knowledge of the damping ratios of the rover's pitch and roll modes is used to specify the filter's characteristics. The maximum deviation of the added noise is chosen to produce and appropriate amount of tilt. Typically a 10° maximum deviation for both in-path and cross-path slopes produces reasonable results.

2. Range Measurement Noise

To simulate the effects of noise corrupted range measurements on system performance, unfiltered white noise is added to each measurement during every scanning operation. A suggested part of any system evaluation is to determine the maximum amount of noise in these measurements that can be tolerated before severe degrading of the system's performance is encountered. This can be estimated by running several simulations using this noise effect alone and increasing the maximum deviation of the added noise in each simulation until the system can no longer detect obstacles in its path.

3. Slope Measurement Noise

During any simulation the path selection system is provided with the values of the vehicle's in-path and cross-path slopes as it moves across the test terrain. This simulates the information that would be available from on-board accelerometer measurements of the vehicle's pitch and roll orientations. Slope measurement noise is a term used in this report for the addition of noise to these measurements. The effect is simulated by adding unfiltered white noise to the values of the vehicle's in-path and cross-path slopes that are made available to the system. This effect should be employed if the system that is being evaluated uses these measures of vehicle orientation in the course of its processing. A suggested part of this type of system's evaluation is to determine how much noise can be tolerated in these measurements before severe degrading of performance occurs.

The procedure used in the test sequences has been to first examine the functioning of the system in the absence of noise and, if the performance is satisfactory, to repeat the sequence with the addition of noise effects. Noisy performance is examined using all noise effects simultaneously after appropriate noise levels for each effect has been determined by simulation.

B. Obstacles

The principle types of obstacles available in the simulation are spherical or drum shaped boulders and spherical craters. Though at first glance it may appear that the simulated boulders and craters are poor characterizations of the real thing, this description is adequate for testing a path-selection system's obstacle avoidance behavior and requires less computer time than a more elaborate description. The boulders selected for use in the test terrains have height-to-diameter ratios of unity. Boulders with heights of 2/3 and 2 meters, respectively, were used for analysis purposes. The 2/3 meter size is roughly on the order of the maximum step height that the rover can handle and represents a lower bound on boulder obstacle sizes. Larger sizes were not used as it was felt that they would be too easily detected to be useful.

The craters selected for use in the test terrains have depth-to-diameter ratios of 1/3 and are used in diameters of 1, 3, and 9 meters. The first case represents a lower bound for the crater to be considered an obstacle, whereas the second case has dimensions on the order of the vehicle's dimensions. The largest size is roughly three times the size of the vehicle and is therefore large enough and deep enough to represent a serious hazard to the vehicle.

C. Standard Testing Procedure

The sequence of test terrains outlined in this report examines the obstacle avoidance behavior of a path selection system under a variety of ideal and non-ideal conditions. The testing begins with relatively simple avoidance problems involving a single boulder or crater and proceeds to more complicated situations. Each avoidance problem is repeated on several different base terrains in order to enable assessment of the effects of in-path and cross-path slopes on the system's functioning. In every case the noiseless performance of the system is first examined. If the performance is satisfactory, the case is repeated with the addition of noise.

In the test terrain sequences heavy emphasis is placed on obtaining information from single obstacle encounter situations. Available Mariner photographs (Ref. 2) of the Martian surface indicate a chaotic, lunar-like landscape with a high incidence of craters, rilles, and depressions. Though terrain data for resolutions on the order of 50 meters is unavailable, it seems reasonable to require that a path selection system be capable of avoiding a single boulder or crater of moderate size in a variety of slope settings.

The simplicity of a terrain containing a single obstacle makes the effect on a system's obstacle avoidance behavior of changing a system parameter much easier to determine. The system's avoidance performance can easily be evaluated on the basis of the clearance that is maintained as the vehicle travels past the obstacle and the distance from the obstacle at which avoidance behavior is first exhibited.

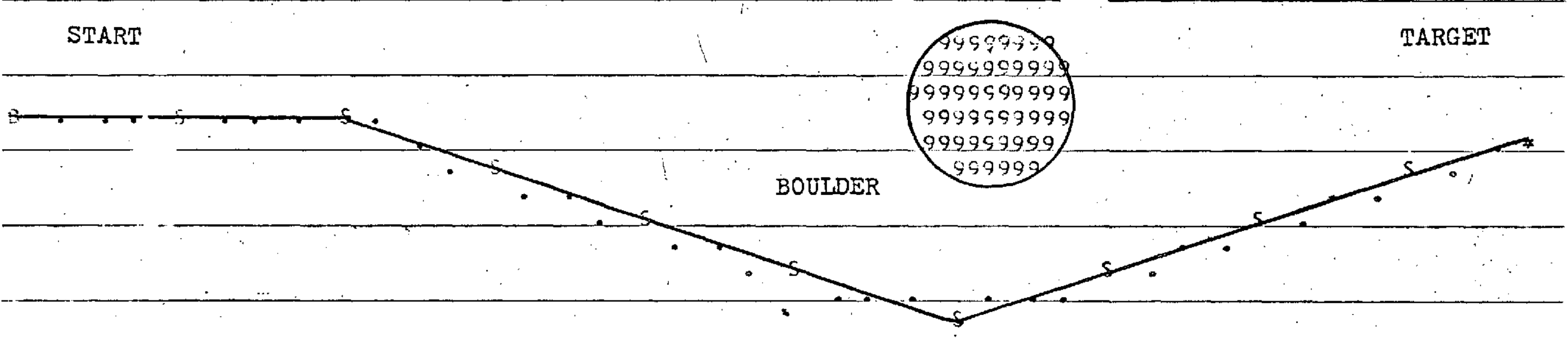
In general, terrains involving a single encounter situation result in a simulation that produces a good deal of information and requires much less computer time than a more complicated terrain characterization. In the test terrain sequences outlined below satisfactory performance on these basic terrains is required before performance on more complicated multi-obstacle terrains is examined.

1. Single Obstacle Encounters on Flat Base Terrain

In this basic avoidance situation shown in Fig. II-1, a single boulder or crater is placed directly on the anticipated line of travel from the vehicle's initial position to the specified target position. The initial position is chosen such that the boulder or crater is beyond the sensor's range on the first scan. The target is positioned so as to be attainable and also minimize the length of the anticipated vehicle path. This shortens the amount of computer time necessary for the simulation and thereby reduces its cost. If the performance is satisfactory, the same cases are repeated with the addition of noise effects. The range at which the system begins active avoidance and the closest approach of the vehicle to the obstacle are recorded for each case and are used as a measure of avoidance performance*.

The simplicity of this test terrain makes it especially suited for examining the effects of parameter changes on system performance and it should be used to examine and set noise levels for the random effects used in the simulations. Successful performance on this basic terrain

*In addition a quantitative indicator of performance is available in each simulation in the form of a figure of merit. See "Performance Evaluation" in Section IV-B for a detailed description.



SINGLE BOULDER ENCOUNTER (FLAT BASE TERRAIN)

Fig. II-1

is required before the effects of varying the base terrain are examined.

2. Single Obstacle Encounters on Rolling Base Terrains

a) Gently Rolling Terrain

In this testing sequence the terrain shown in Fig. II-2 is used to examine system performance in the presence of the type of non-zero in-path and cross-path slopes found in a gently undulating terrain. The system's noiseless functioning is examined first. The initial position and target position are chosen to provide non-zero in-path and cross-path slopes by angling across the terrain, or just in-path slopes by moving in the x-direction only*. A case with no obstacles is run to determine the vehicle path to the target and to serve as a base line in predicting when avoidance behavior begins. A single boulder or crater is then placed directly in the vehicle's path to the target and the procedure outlined for the flat base terrain sequence is followed. If the performance is satisfactory the same cases are repeated with the addition of noise.

b) Rolling Incline

In this testing sequence the terrain shown in Fig. II-3 is used to examine system performance in the presence of the type of non-zero in-path and cross-path slopes encountered on the side of a hill. The incline has a maximum in-path slope of 18° to 20° and presents no hazard to vehicle travel. Both uphill and downhill approaches

*In the coordinate system used in the terrain contour maps shown in the figures throughout this report, the x-axis runs from left to right across the page and the y-axis from the bottom to the top of the page. The z-axis points out of the page and elevations are represented by numbers and blanks.

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-2.00 (METERS)
 3.00 (METERS)         9.85                      16.71                       23.56                      30.41                    37.00
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9999999999   88   7 66 5   4 33 22 11   0000000000   11 22 33 4   5 66 77 88   9999999999   88 77 66 5   4 33 2   11   0000000000
9999999999   88   7 66 5   4 33 22 11   0000000000   11 22 33 4   5 66 77 88   9999999999   88 77 66 5   4 33 2   11   0000000000
9999999999   88   7 66 5   4 33 22 11   0000000000   11 22 33 4   5 66 77 88   9999999999   88 77 66 5   4 33 2   11   0000000000
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9999999999   88   7 66 5   4 33 22 11   0000000000   11 22 33 4   5 66 77 88   9999999999   88 77 66 5   4 33 2   11   0000000000
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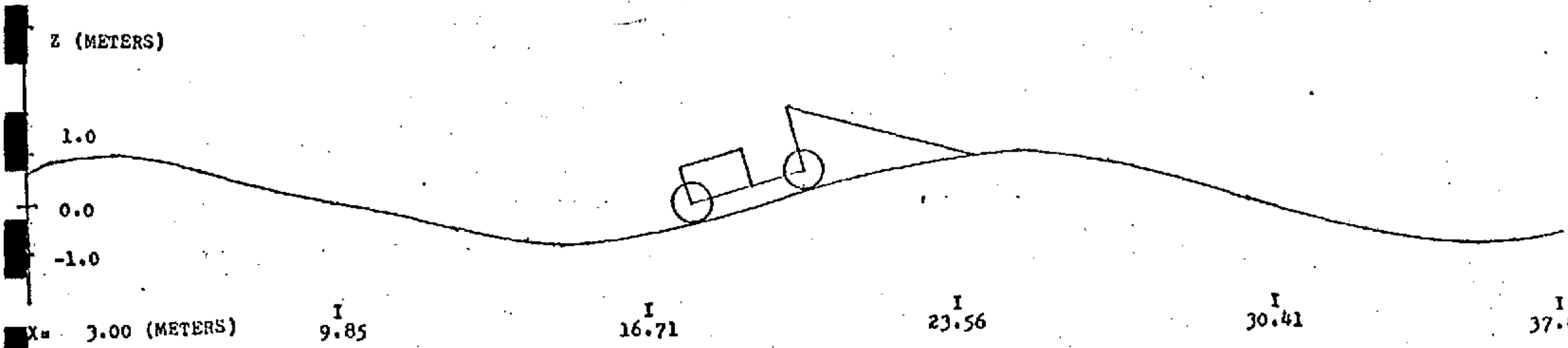
9999999999   88   7 66 5   4 33 22 11   0000000000   11 22 33 4   5 66 77 88   9999999999   88 77 66 5   4 33 2   11   0000000000

                         I                          I                          I                          I                          I
X=  3.00 (METERS)      9.85                      16.71                       23.56                      30.41                    37.00
Y= -17.00 (METERS)
```

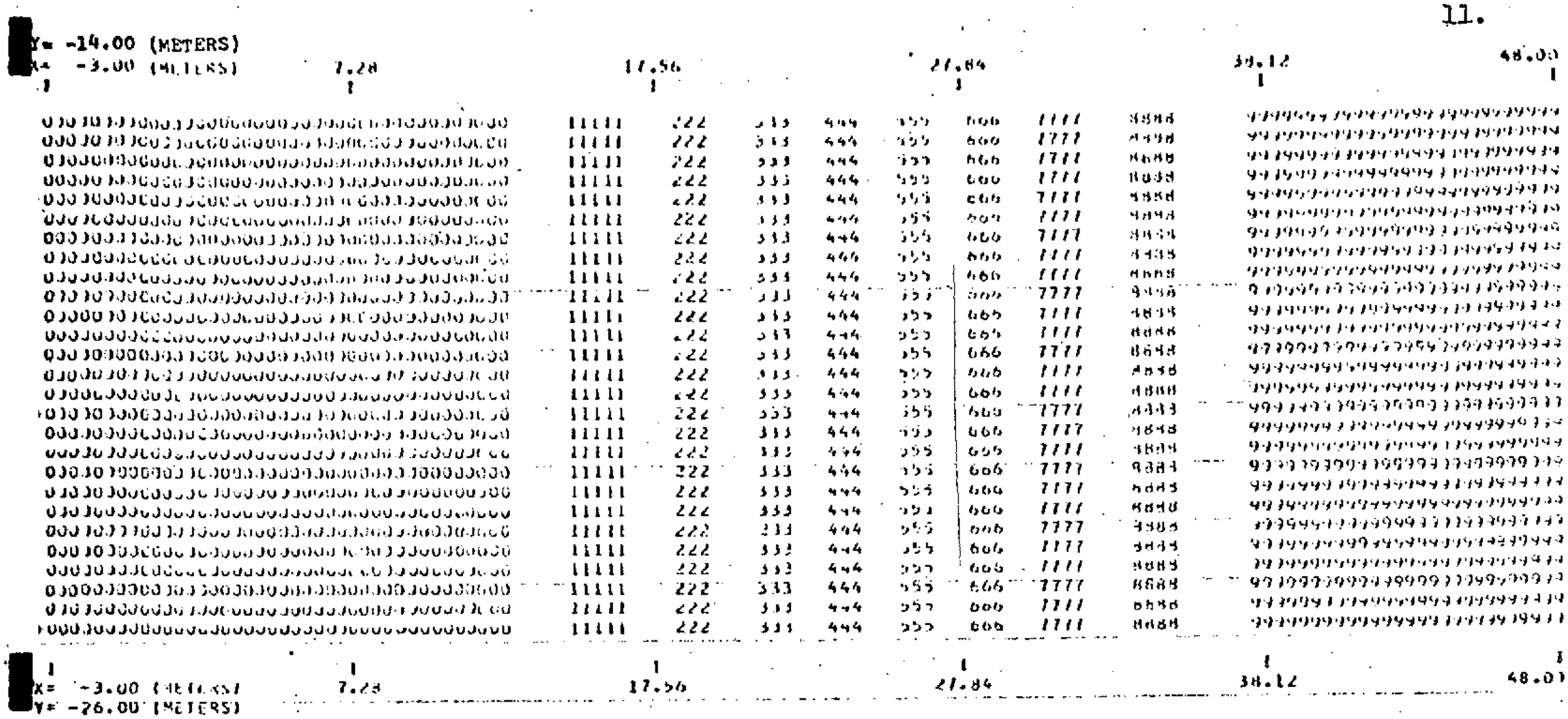
SYMBOL	0	1	2	3	4	5	6	7	8	9
RANGE OF ALTITUDES (METERS)	-1.01 TO -0.90	-0.80 TO -0.69	-0.58 TO -0.48	-0.37 TO -0.27	-0.16 TO -0.05	0.05 TO 0.16	0.27 TO 0.37	0.48 TO 0.58	0.69 TO 0.80	0.90 TO 1.01

CROSS-SECTIONAL
PROFILE



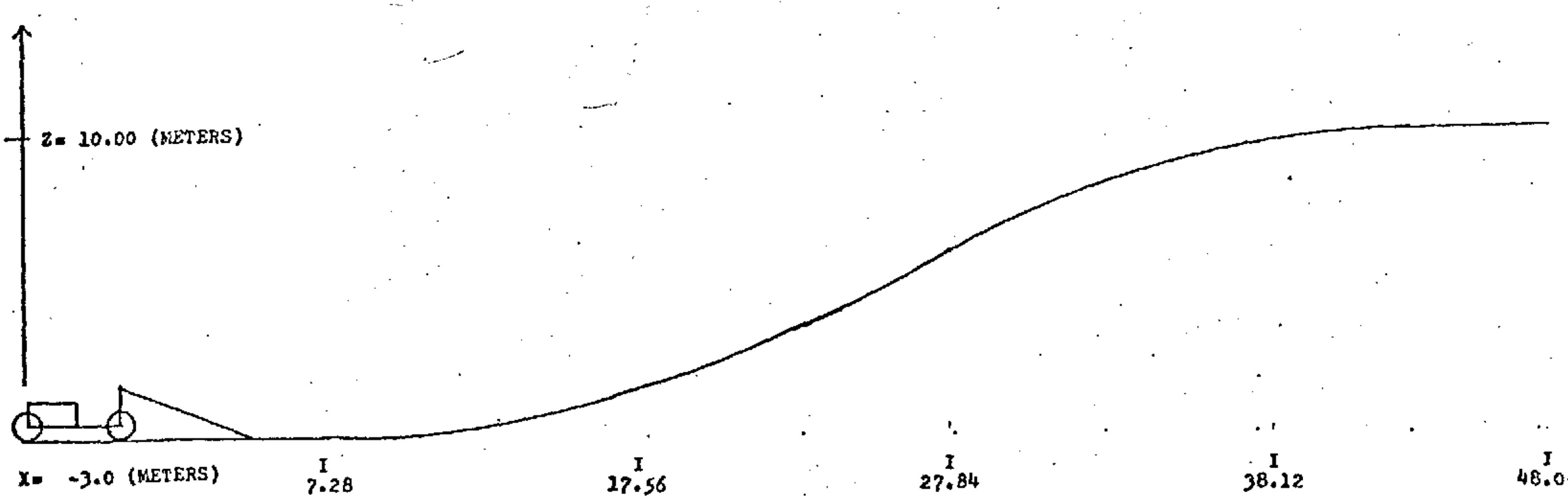
GENTLY ROLLING TERRAIN

Fig. II-2



SYMBOL	0	1	2	3	4	5	6	7	8	9
RANGE OF ALTITUDES (METERS)	-0.05 TO 0.96	1.01 TO 1.54	2.04 TO 2.61	3.14 TO 3.67	4.20 TO 4.73	5.27 TO 5.80	6.33 TO 6.86	7.39 TO 7.92	8.45 TO 8.99	9.52 TO 10.05

CROSS-SECTIONAL
PROFILE



ROLLING INCLINE

Fig. II-3

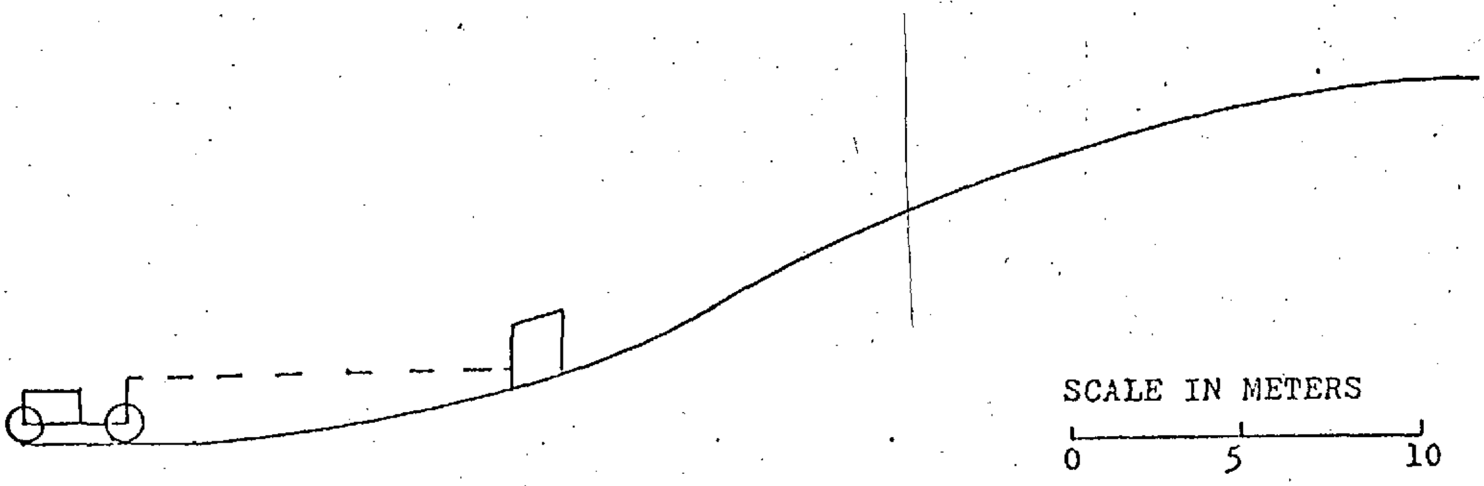
are possible. The choices of initial vehicle position and target position allow a variety of in-path and cross-path slopes to be encountered as the vehicle proceeds to the target. First a case without obstacles is run to determine the path to the target and to serve as a base line in establishing when avoidance behavior begins. A single boulder or crater is then placed on the vehicle's path and the procedure outlined in the flat base terrain sequence is followed. The choice of the obstacle's position is based upon finding situations along the vehicle path to target where the effects of in-path and cross-path slopes make detection difficult. Figure II-4 shows two possible uphill cases for a path parallel to the x-axis. In the first situation the presence of the boulder is masked by the hill in the background. In the second situation the sensor beam is tilted above the obstacle's location.

3. Multi-Obstacle Cases

The previous sequences examined the system's performance in avoiding single obstacles in a variety of slope settings and in the presence and absence of noise. The next sequence of terrains assumes the system has proved it can successfully avoid single obstacles, and presents the system with more complicated avoidance problems to solve. All these terrains require longer paths to target involving the successful avoidance of several obstacles in a variety of slope settings. All cases are run in the presence of noise.

a) Two Obstacle Key-Hole Problem

In this simple avoidance problem shown in Fig. II-5 the system must choose between traveling through the "key-hole" formed by two boulders, or craters, or circling around the obstacles to reach

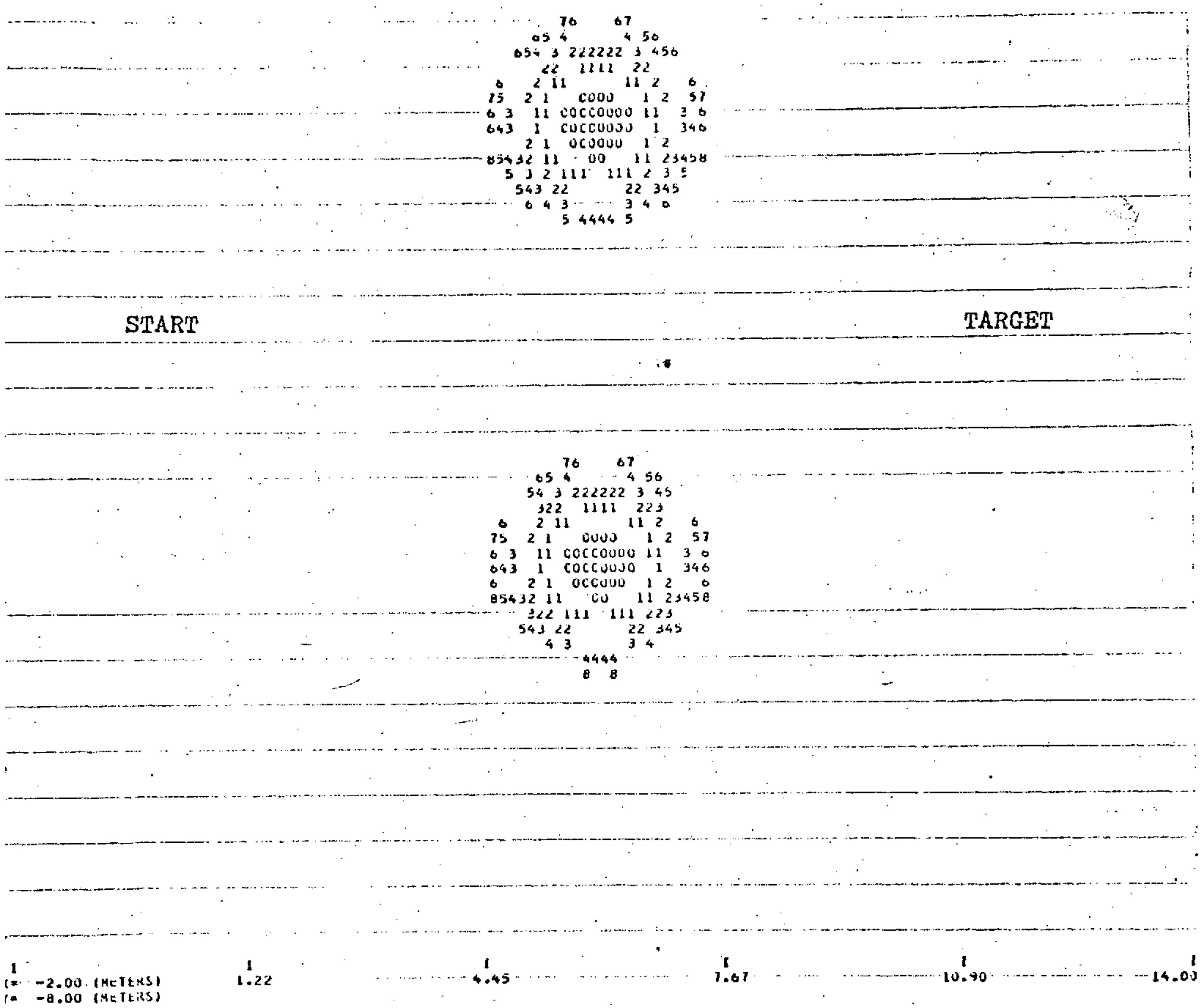


CASE 1

CASE 2

SINGLE OBSTACLE ENCOUNTERS
(ROLLING INCLINE)

Fig. II-4



SYMBOL	0	1	2	3	4	5	6	7	8	9
RANGE OF ALTITUDES (METERS)	-1.00 TO -0.95	-0.89 TO -0.83	-0.78 TO -0.72	-0.66 TO -0.60	-0.55 TO -0.49	-0.43 TO -0.38	-0.32 TO -0.26	-0.21 TO -0.15	-0.09 TO -0.03	0.02 TO 0.08

KEYHOLE PROBLEM

Fig. II-5

target. Two variations are possible with this problem. In the first, the obstacles are positioned to make the key-hole wide enough to be a safe path to target. In this case the correct solution to the problem is to travel through the key-hole to reach the target. The indicators of system performance are the time to travel to target, the length of the chosen path and the closest approach to an obstacle.

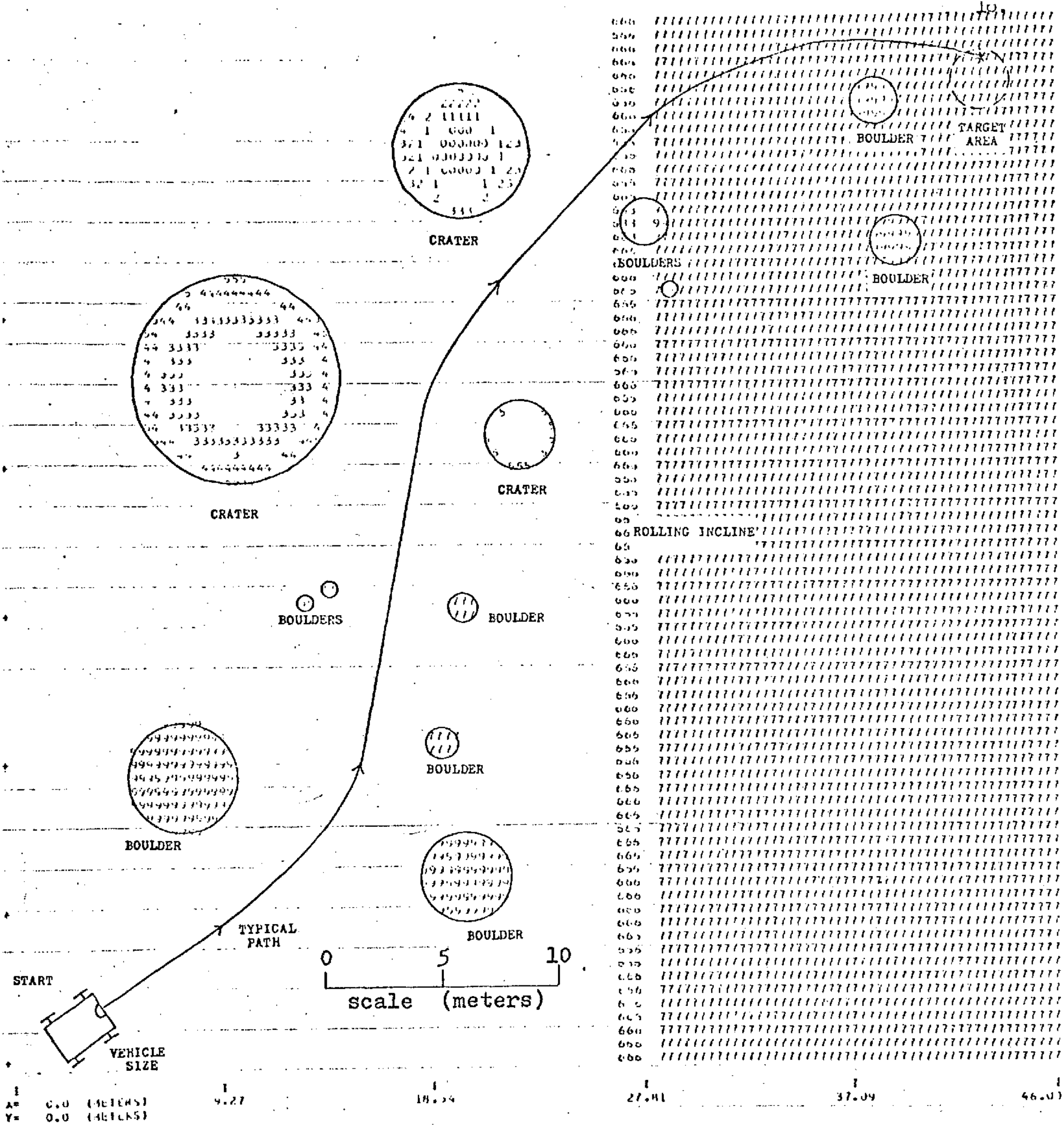
In the second arrangement the obstacles are placed close enough together to make the path through the key-hole not wide enough to be considered safe. In this case the correct solution is to circle the obstacles to target. The indicator of system performance in this simulation is the closest approach to an obstacle.

b) <u>Boulder Crater Field</u>

Figure II-6 shows a maze-like arrangement of boulders and craters of various sizes lying at the base of a 2 meter hill. There are several possible paths through the field and the average path length to the target is anticipated to be 50 to 80 meters. Filtered white noise is used during the simulation to create the effect of rubble strewn on the base terrain varying in size up to a maximum of 0.1 meters. The indicators of system performance in this simulation are the time to travel to the target, the length of the chosen path, and the closest approach to an obstacle.

b) <u>Box Canyon</u>

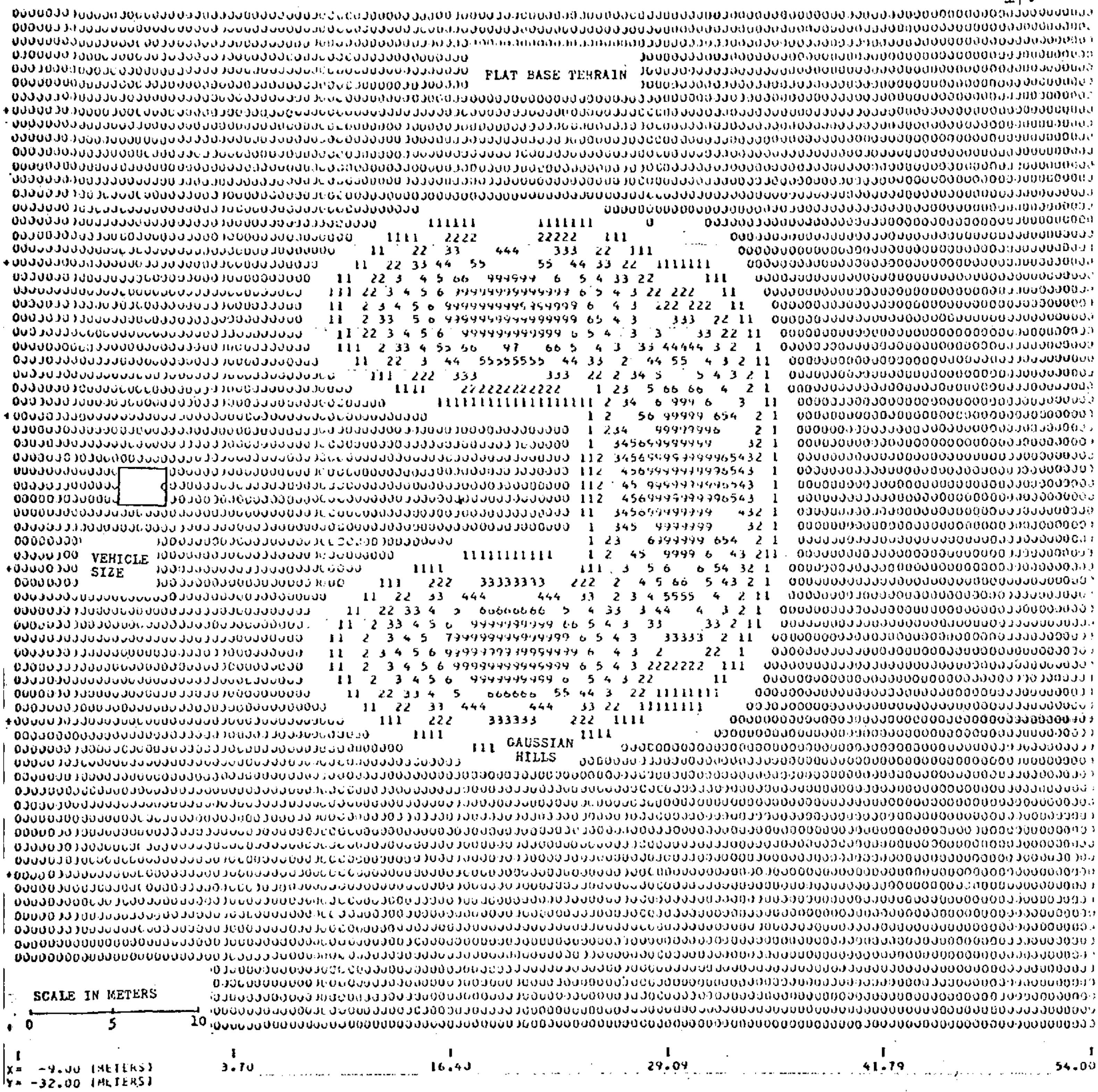
Figure II-7 shows a box canyon formed by three Gaussian hills, each too steep to be climbed. The vehicle must back out of the canyon and circle the hills to reach target.



SYMBOL	0	1	2	3	4	5	6	7	8	9
RANGE IN ALTITUDES (METERS)	-5.61 TO -5.13	-4.62 TO -4.11	-3.60 TO [illegible]	-2.58 TO -2.07	-1.56 TO -1.05	-0.54 TO -0.03	0.49 TO [illegible]	1.53 TO 2.01	2.52 TO [illegible]	3.54 TO [illegible]

BOULDER-CRATER FIELD

Fig. II-6



SYMBOL	0	1	2	3	4	5	6	7	8	9
RANGE OF ALTITUDES (METERS)	-0.15 TO 0.76	2.03 TO 3.09	4.15 TO 5.22	6.28 TO 7.34	8.41 TO 9.47	10.53 TO 11.59	12.66 TO 13.72	14.78 TO 15.85	16.91 TO 17.97	19.04 TO 20.1[illegible]

BOX CANYON

Fig. II-7

D. Conclusions and Recommendations

The test terrains that have been developed to date place heavy emphasis on single obstacle encounters in a variety of slope settings and in the presence and absence of noise effects. Satisfactory performance on these basic terrains is required before performance on more complicated multi-obstacle terrains is examined. The development of single obstacle encounter terrains has been essentially completed and future work should concentrate on the development of additional multi-obstacle terrains.

III. EVALUATION OF A MID-RANGE SENSOR SYSTEM

The mid-range sensor system evaluated in this section was proposed by the navigational computer group at Cornell University in 1972. A brief description of the system is presented below. The development of this system is discussed in greater length in Ref. 3.

In evaluating the system it was first necessary to incorporate the system features into the computer simulation package. The next step was to carry out a sequence of simulation runs. These simulations were performed using the guidelines of the standard testing procedure described in Section II. Finally, based on the simulation results the system's performance was evaluated and recommendations directed at improving the system design are presented in Part D of this section.

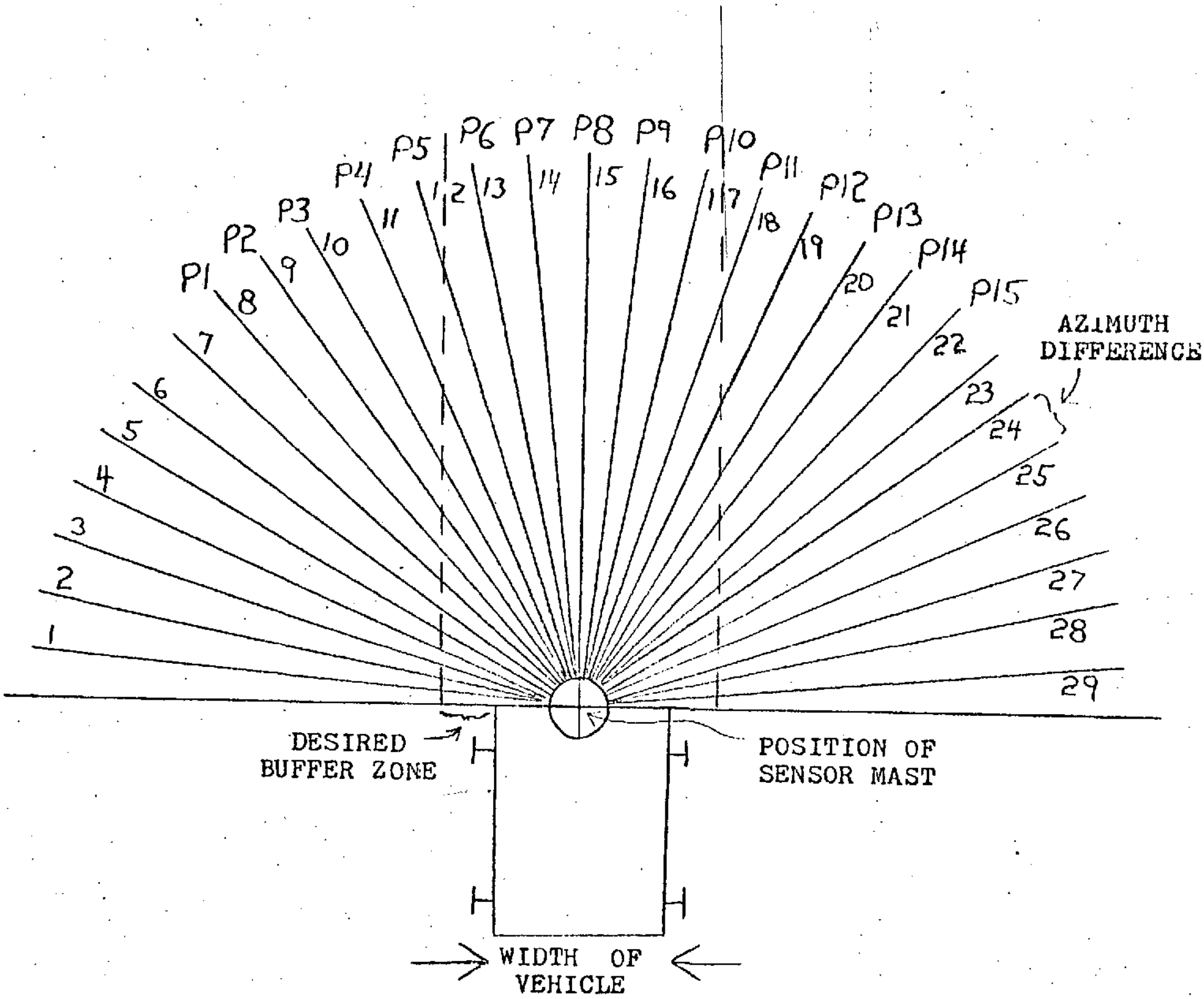
A. System Description

The proposed path selection system, as represented in the simulation package, is divided into three distinct operations: the sensor, the terrain modeler, and the path selection algorithm. A description of each operation follows:

1. Sensor

A sensor which measures ranges up to ten meters is simulated. The sensor is mounted on a vertical mast fixed to the front of the vehicle. The mast height above ground level is specified by the program user. Sensor orientation is calculated by taking into account the effects of in-path and cross-path slopes at the vehicle's current position.

During each sensor scan a single beam, which moves in a plane perpendicular to the mast, uniformly sweeps the area in front of the vehicle (see Fig. III-1). At each scan twenty-nine range measurements



SENSOR SCAN (TOP VIEW)

Fig. III-1

are made. The scan time is assumed to be instantaneous and the time between sensor scans is two seconds. The number of degrees between successive beam shots is uniform and defined as the azimuth difference.

The mid-range sensor is designed primarily to detect large positive obstacles. However, in addition to the mid-range sensor, an ideal mechanical sensor is simulated. If the mid-range system fails to detect a dangerous obstacle this sensor acts as a system override. The mechanical sensor is simulated by computing, at each half meter increment of travel, the slope between a point located directly beneath the center of the front edge of the vehicle and a point on the surface which is one-half meter in front of the vehicle. If the magnitude of this slope is greater than thirty degrees then the emergency mode is called.

2. Terrain Modeler

This process operates on the range measurements received from the sensor simulator. The modeler assigns to the fifteen forward paths P1, P2,...,P15, either a value of unity, to represent an acceptable path, or a value of zero, to represent an unacceptable path.

In order for a given forward path to be rated as acceptable the range measurement for that path, and the measurements for the seven adjoining paths on each side, must be within certain computed thresholds. This set of minimum range values is computed using the formula:

$$R_i = \frac{\frac{1}{2} W + B}{\cos \theta_i}, \qquad \text{for all } \theta_i \neq \pi/2$$

where:

R_i = minimum range value for path being analyzed (meters).

W = specified vehicle width (meters).

B = desired buffer zone (meters).

θ_i = angle of path with respect to front edge of vehicle (radians).

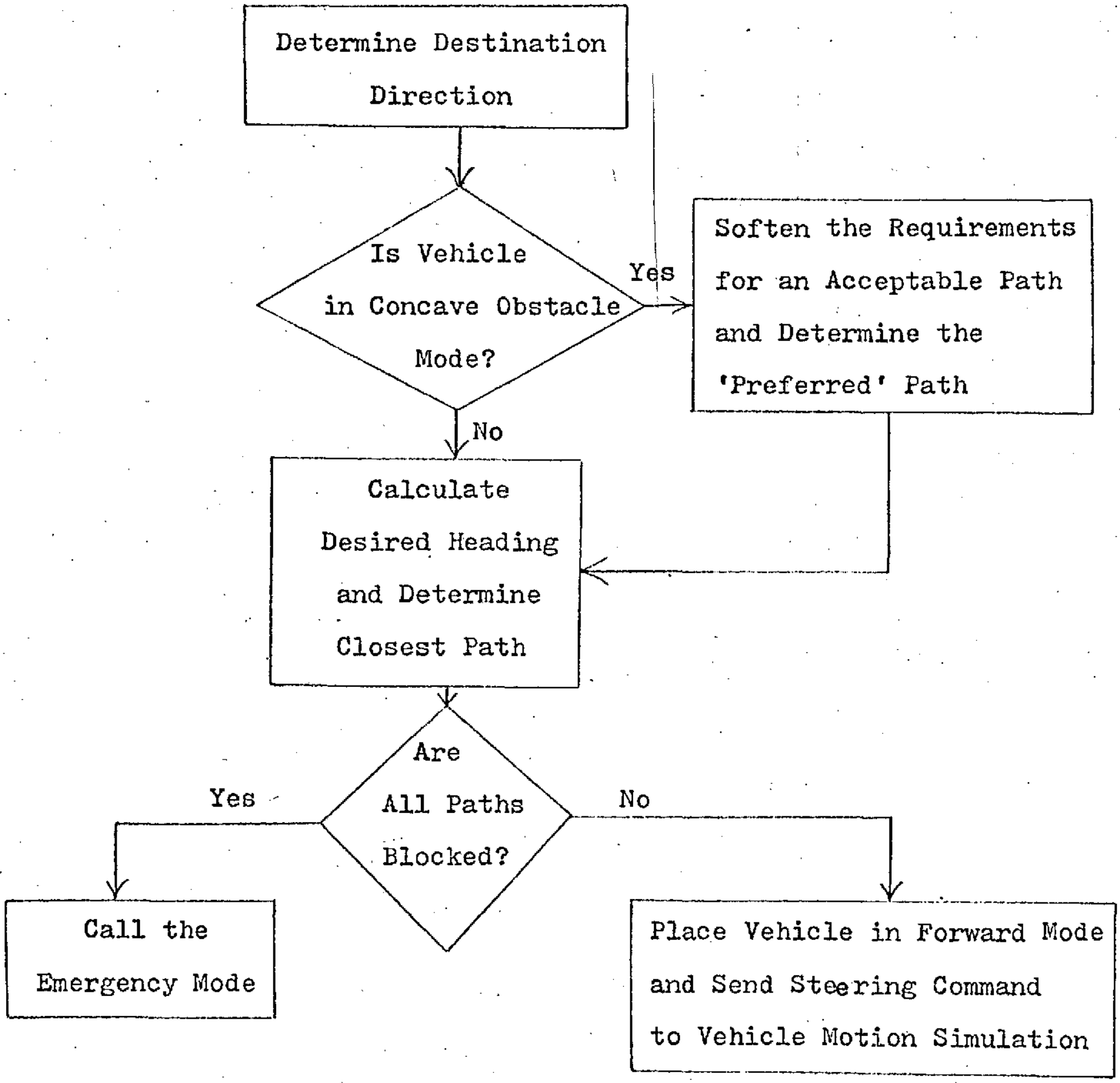
Figure III-1 shows the locations of these variables with respect to the location of the vehicle. The minimum range value is set at eight meters for $\theta_i = \pi/2$ and for all other computed minimum range values which are greater than eight meters. Since the vehicle travels about two meters between sensor scans and the maximum range threshold value is eight meters, then the vehicle is expected to begin obstacle avoidance at a distance of between six and eight meters from a detectable obstacle, in the absence of the effects of random disturbances.

3. Path Selection Algorithm

A block diagram representation of the path selection algorithm is shown in Fig. III-2. In normal operation the path selection algorithm chooses the closest acceptable path to target. If all of the paths are blocked the emergency mode is called and the following steps are taken:

1) the vehicle is backed up in a straight line,
2) a new sensor scan is taken,
3) the seven forward paths P5, P6,...,P11 are blocked, and
4) the closest acceptable path to target is again selected.

A special feature of the path selection algorithm is the concave obstacle mode. This mode was specifically designed to aid the vehicle in reaching its destination if trapped by obstacles forming a concave blockade. When in this mode the maximum allowed minimum range value is reduced from eight to five meters. Then depending on the previous turn made and the present quadrant of the destination direction either the extreme left or extreme right path is chosen. Table III-1 contains a summary of the concave obstacle mode decisions.



PATH SELECTION ALGORITHM

Fig. III-2

TABLE III-1. CONCAVE OBSTACLE MODE DECISIONS

PREVIOUS TURN MADE	PRESENT QUADRANT OF DESTINATION DIR.				NEXT PATH TO BE CHOSEN
	FRONT RIGHT	REAR RIGHT	FRONT LEFT	REAR LEFT	
NEITHER				X	LEFT
			X		NEITHER
		X			RIGHT
	X				NEITHER
RIGHT				X	LEFT
			X		NEITHER
		X			LEFT
	X				LEFT
LEFT				X	RIGHT
			X		RIGHT
		X			RIGHT
	X				NEITHER

B. Simulation Procedure

The simulation and evaluation of the proposed system was performed in a systematic fashion, corresponding to the guidelines of the standard test procedure described in Section II. Over forty simulation runs were made examining the system's deterministic performance and its performance in the presence of attitude noise. No examination of the effects of range measurement or slope measurement noise has been made to date.

Since the system was designed to detect positive obstacles, a systematic testing with craters was not performed. The presence of all negative obstacles is assumed to be detected by the ideal mechanical sensor.

During the simulation procedure three system parameters, namely, the sensor mast height, the specified buffer zone, and the azimuth difference were varied to determine how these parameters affect system performance.

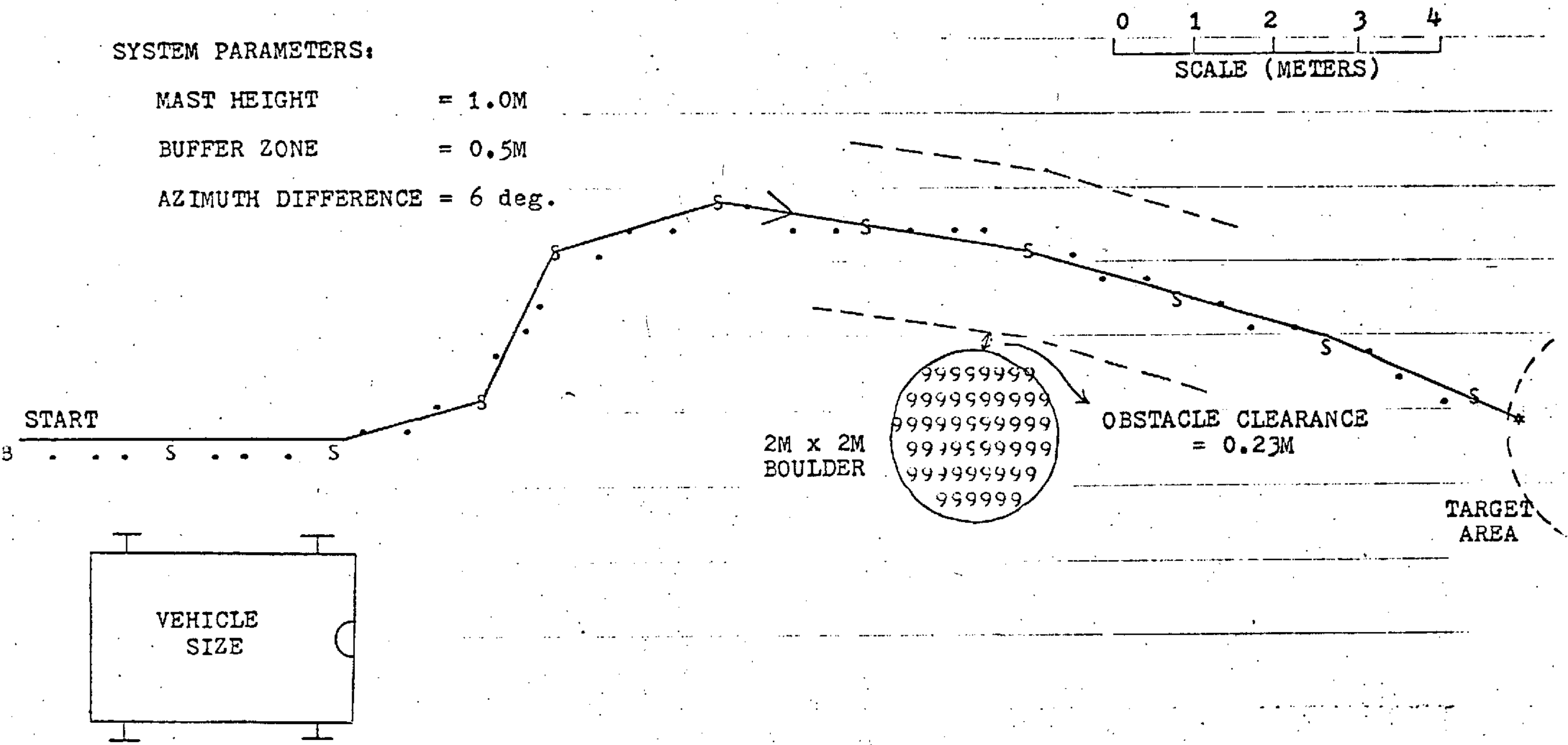
C. Simulation Results

The simulation results are presented in three categories: single-boulder encounters, multi-obstacle cases, and special terrains. A summary of the performance of the mid-range sensor system in each category is given below.

1. Single-Boulder Encounters

a) Flat Base Terrain

In encounters with the 2 x 2 meter boulder the vehicle always made a successful pass around the obstacle. However, in the presence of attitude noise the vehicle sometimes took an erratic path to target. As an example consider Fig. III-3. The system detects the boulder when the vehicle is seven meters away and steers gently left. However, at the next scan attitude noise has tilted the sensor mast ten degrees forward, driving the scans into the ground. As a



SINGLE BOULDER ENCOUNTER (NOISE)

Fig. III-3

result, the vehicle is fooled into believing there is an obstacle directly in front of itself and steers sharply left.

In encounters with the smaller boulder (2/3 x 2/3 meters) system performance was not always satisfactory. In the absence of noise the vehicle often lost sight of the boulder between scan shots, causing a collision. It was determined that, in order to avoid such collisions, the azimuth difference must be reduced to three degrees or less. In the presence of attitude noise the situation was further complicated by the fact that scans were sometimes directed over the top of the boulder or into the ground in front of it, blinding the vehicle of the trouble area.

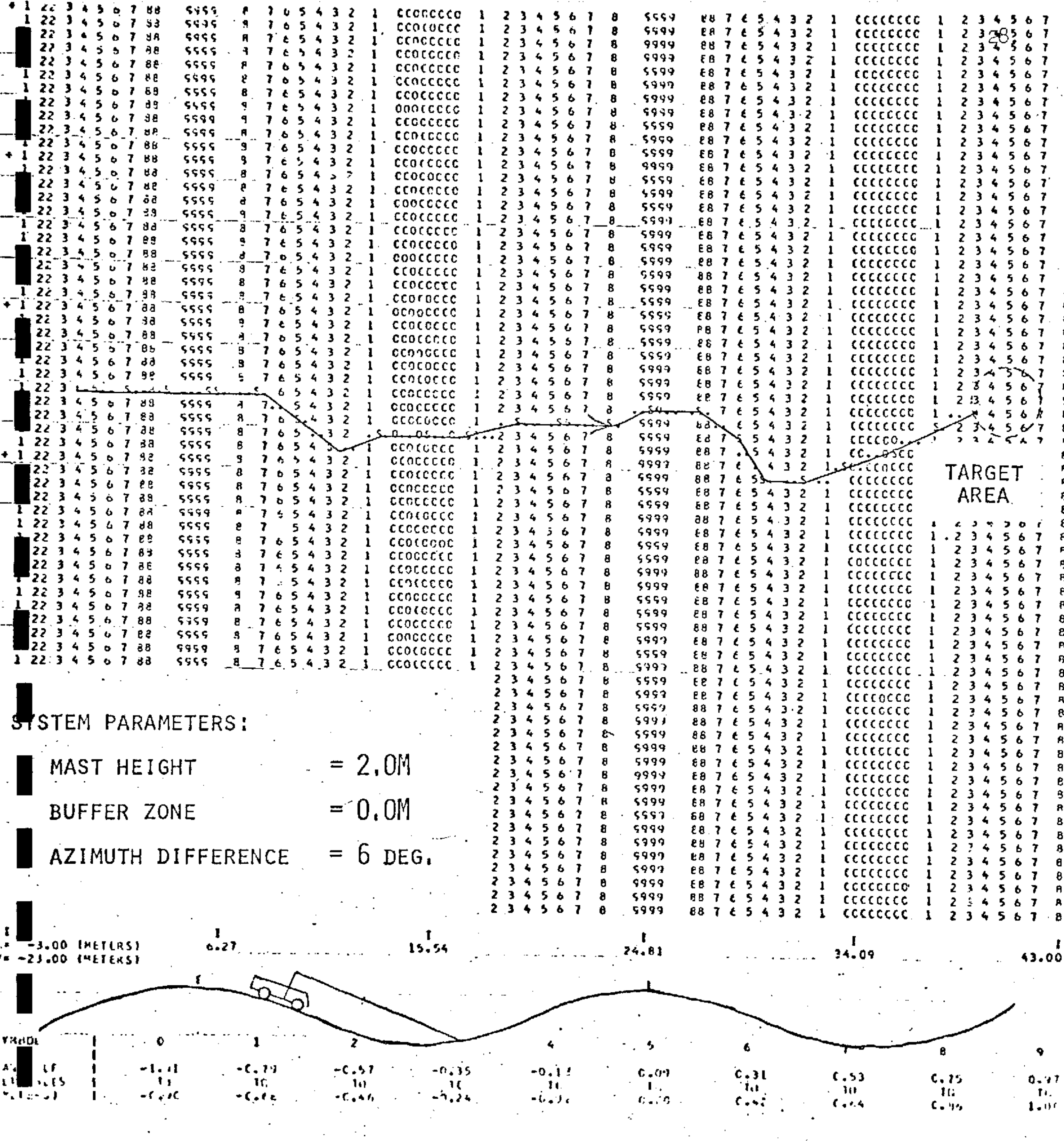
b) Gently Rolling Terrain

Because of the vehicle-fixed mast when the vehicle travels uphill scans point over the hill, whereas when it travels downhill scans point into the next rise. The magnitude of this disturbance is a function of the mast height.

The gently rolling terrain presented little difficulty for a mast height of two meters when no obstacles were encountered (see Fig. III-4). However, with the two meter mast boulders frequently went undetected as scans went over their tops. With smaller mast heights (0.5 and 1.0 meters) the vehicle detected more obstacles, but was forced to traverse the terrain at an angle in order to reduce the magnitude of the in-path slopes. In this testing sequence the best compromise of mast height was estimated to be between one and two meters.

c) Rolling Incline

In this sequence runs were restricted to uphill cases. System



GENTLY ROLLING TERRAIN (NO OBSTACLE)

Fig. III-4

performance was generally good when the boulder placement was near the bottom of the hill. However, when the boulder was placed at the crest of the hill it was never detected by the system, because as the vehicle approached the obstacle the sensor scans were pointing over it due to the in-path slope of the hill. Figure III-5 is an example of a case where a 2 x 2 meter boulder was placed near the bottom of the hill, and Fig. III-6 is an example of a case where a 2/3 x 2/3 meter boulder was placed on the crest of the hill. In the latter case the system fails to detect the boulder, but the ideal mechanical sensor detects it just prior to a collision and triggers a call to the emergency mode.

Throughout the single boulder encounters one of the system parameters varied was the desired buffer zone. Table III-2 contains the average obstacle clearance distances for various values of desired buffer zones. The number of runs averaged is in parenthesis following each value. There are two significant results. First, as the width of the desired buffer zone is increased from one meter to two meters the percentage of actual buffer zone achieved decreased from about 80% to 50%. Secondly, in the presence of noise the vehicle usually passed closer to the obstacle.

A comparison of system performance with two different buffer specifications in a single boulder encounter is shown in Fig. III-7.

2. Multi-Obstacle Cases

In a deterministic run through a field of ten large boulders the vehicle was able to find a short and safe path to target. However, when the system was simulated over a realistic boulder-crater field which

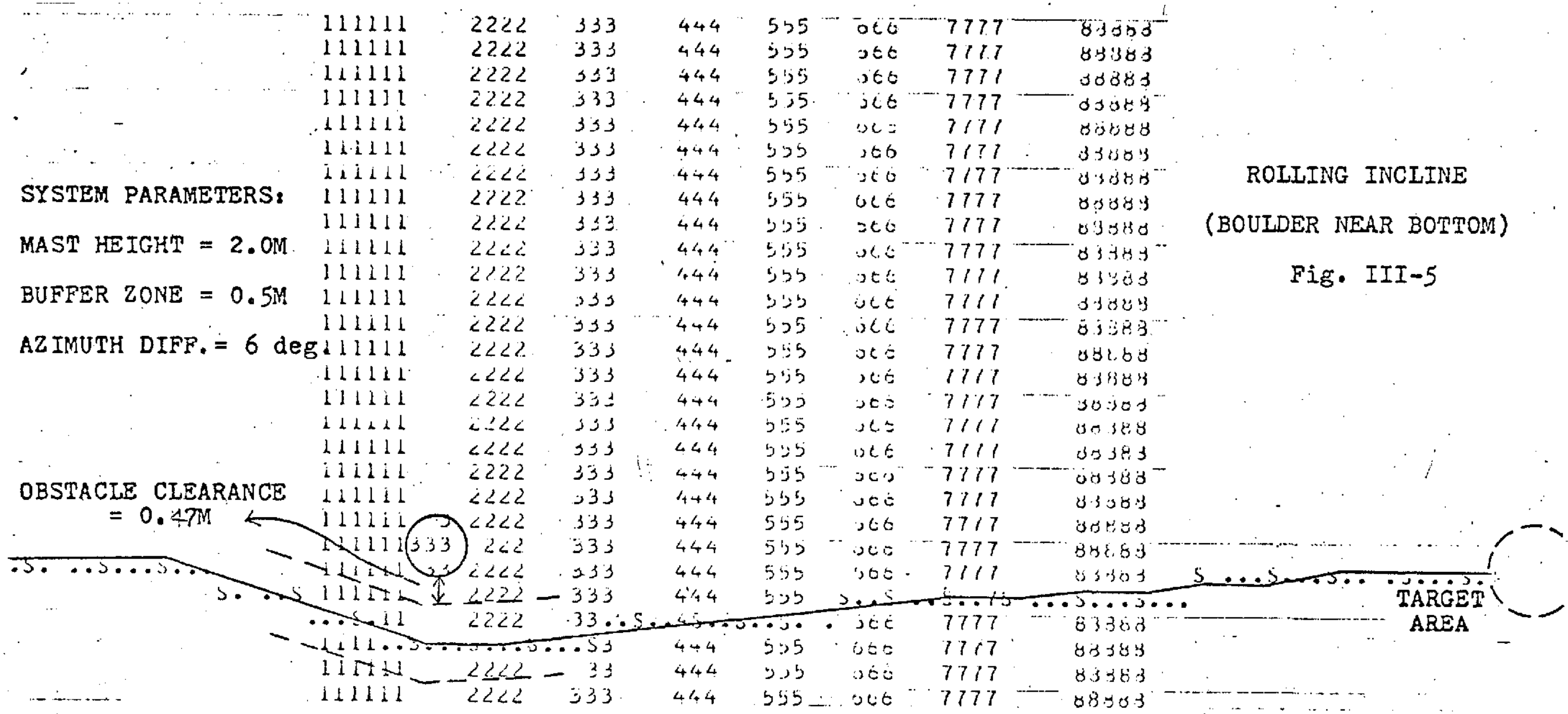
SYSTEM PARAMETERS:

MAST HEIGHT = 2.0M

BUFFER ZONE = 0.5M

AZIMUTH DIFF.= 6 deg.

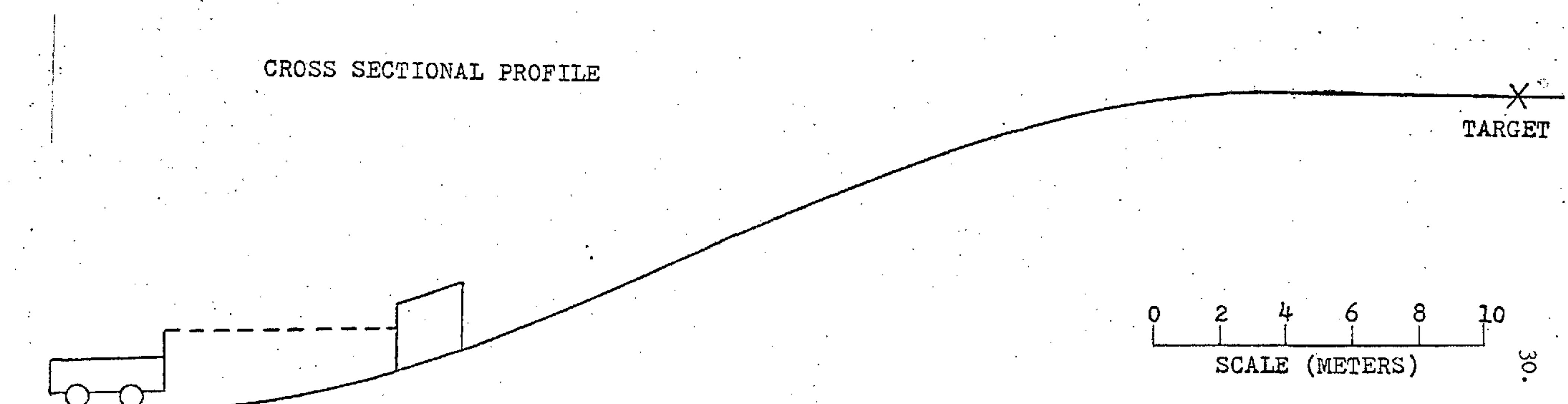
OBSTACLE CLEARANCE
= 0.47M

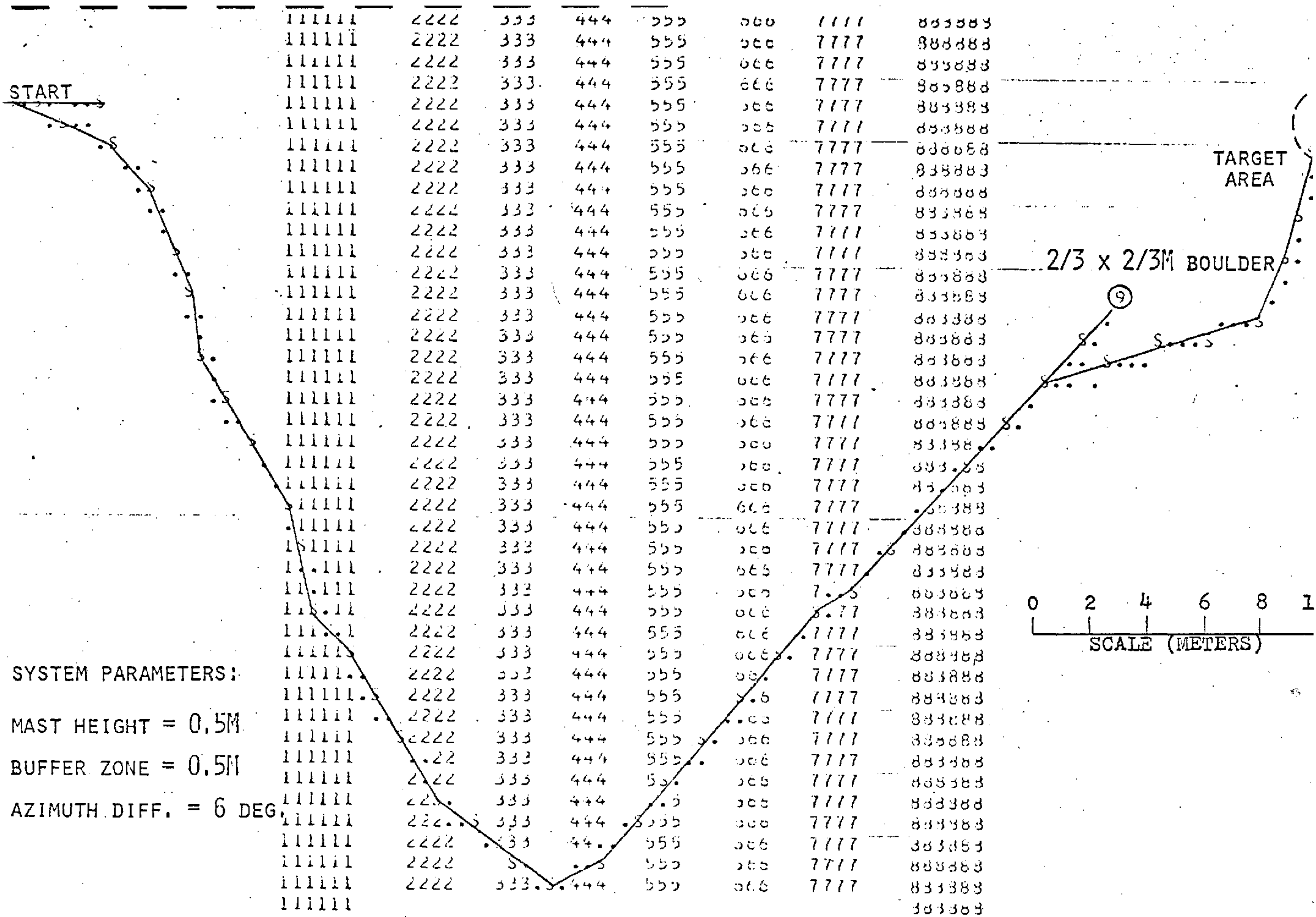


ROLLING INCLINE

(BOULDER NEAR BOTTOM)

Fig. III-5



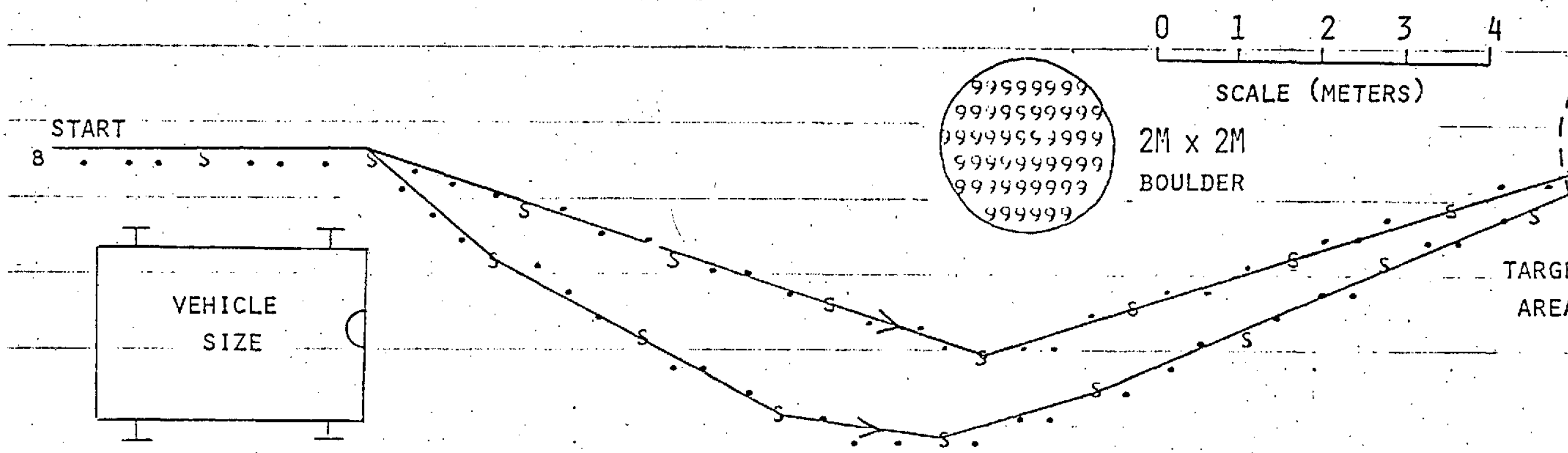


ROLLING INCLINE (BOULDER ON CREST)

Fig. III-6

TABLE III-2. AVERAGE OBSTACLE CLEARANCES

Desired buffer zone (meters)	Average Obstacle Clearances	
	noise	no noise
0.0	0.04 (1)	0.04 (3)
0.5	0.39 (2)	0.46 (3)
1.0	0.68 (3)	0.84 (3)
2.0	0.95 (1)	1.09 (3)



OBSTACLE CLEARANCE =
0.39 AND 1.05 METERS

SYSTEM PARAMETERS:

MAST HEIGHT = 1.0M

BUFFER ZONE = 0.5M (TOP) 2.0M (BOTTOM)

AZIMUTH DIFFERENCE = 6 DEG.

SINGLE BOULDER ENCOUNTER (TWO BUFFER SPECIFICATIONS)

Fig. III-7

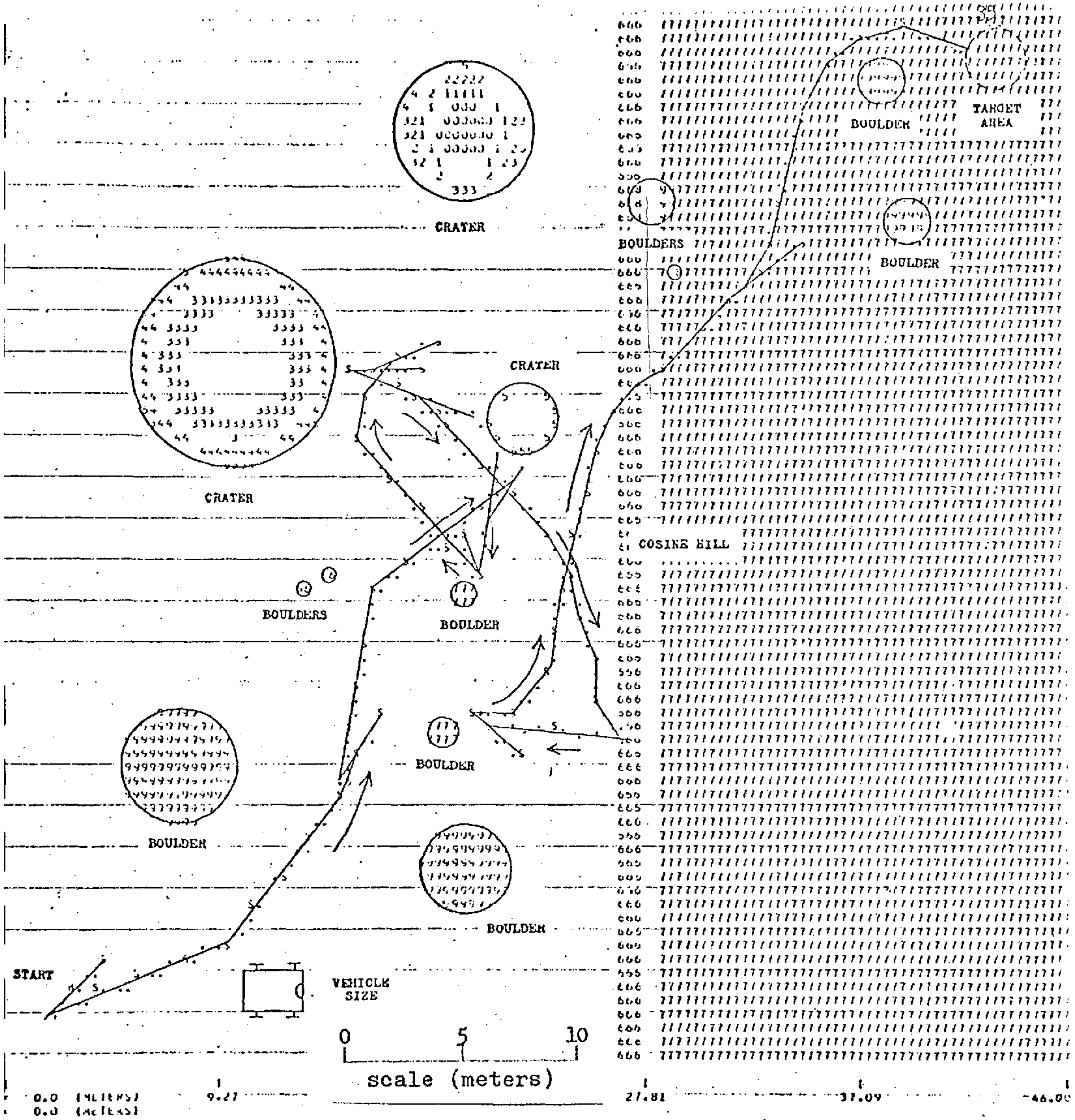
included a small rise and noise, the performance was not as efficient as before (see Fig. III-8). For this simulation a one meter mast height and one half meter buffer zone were specified. The vehicle was eventually able to reach its target despite misinterpreting the small rise as an unnegotiable obstacle and using the emergency mode thirteen times.

3. Special Terrains

A special terrain containing three large boulders and a cliff was designed to challenge the emergency mode of the path selection algorithm. On this terrain the vehicle is faced with two impassable regions and one passable region. As depicted in Fig. III-9 the system failed to find the passable region as the emergency mode repeatedly steered the vehicle back into the trouble area. The problem with the emergency mode is that once a backup maneuver is performed the closest acceptable path to target is again selected, irregardless of the fact that the vehicle had already unsuccessfully tried that path.

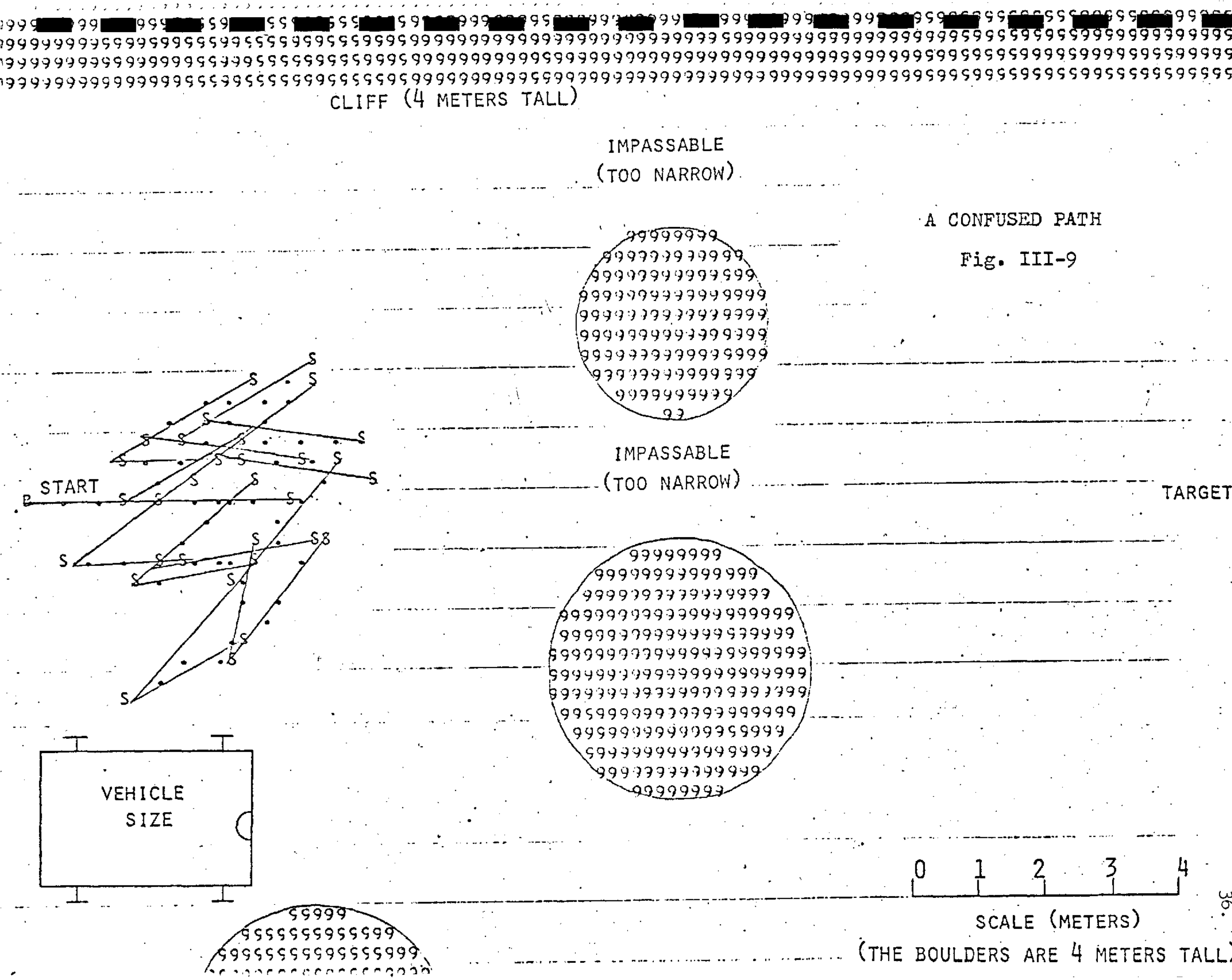
To solve this problem it was concluded that some form of memory capability must be added to the emergency algorithm. Based on this conclusion a new emergency mode was proposed. The new procedure includes the following steps:

1) the vehicle is backed up in a straight line,
2) a preferred side is chosen,
3) a new sensor scan is taken,
4) the seven forward paths and the fourteen unpreferred side paths are blocked, and
5) the terrain modeler is instructed to block the unpreferred side paths for the next three sensor scans.



RANGE	0	1	2	3	4	5	6	7	8	9
[illegible]	-5.66	-4.62	-3.60	-2.59	-1.56	-0.54	0.59	1.59	2.52	3.5[illegible]
[illegible]	11	10	10	10	10	11	10	11	10	11
[illegible]	-5.11	-4.11	[illegible]	-2.07	-1.05	[illegible]	[illegible]	2.01	3.03	4.1[illegible]

BOULDER-CRATER FIELD (WITH NOISE)
Fig. III-8



A CONFUSED PATH

Fig. III-9

As shown in Fig. III-10 the proposed emergency algorithm enabled the vehicle to successfully find the passable region to target with only one backup.

D. Conclusions and Recommendations

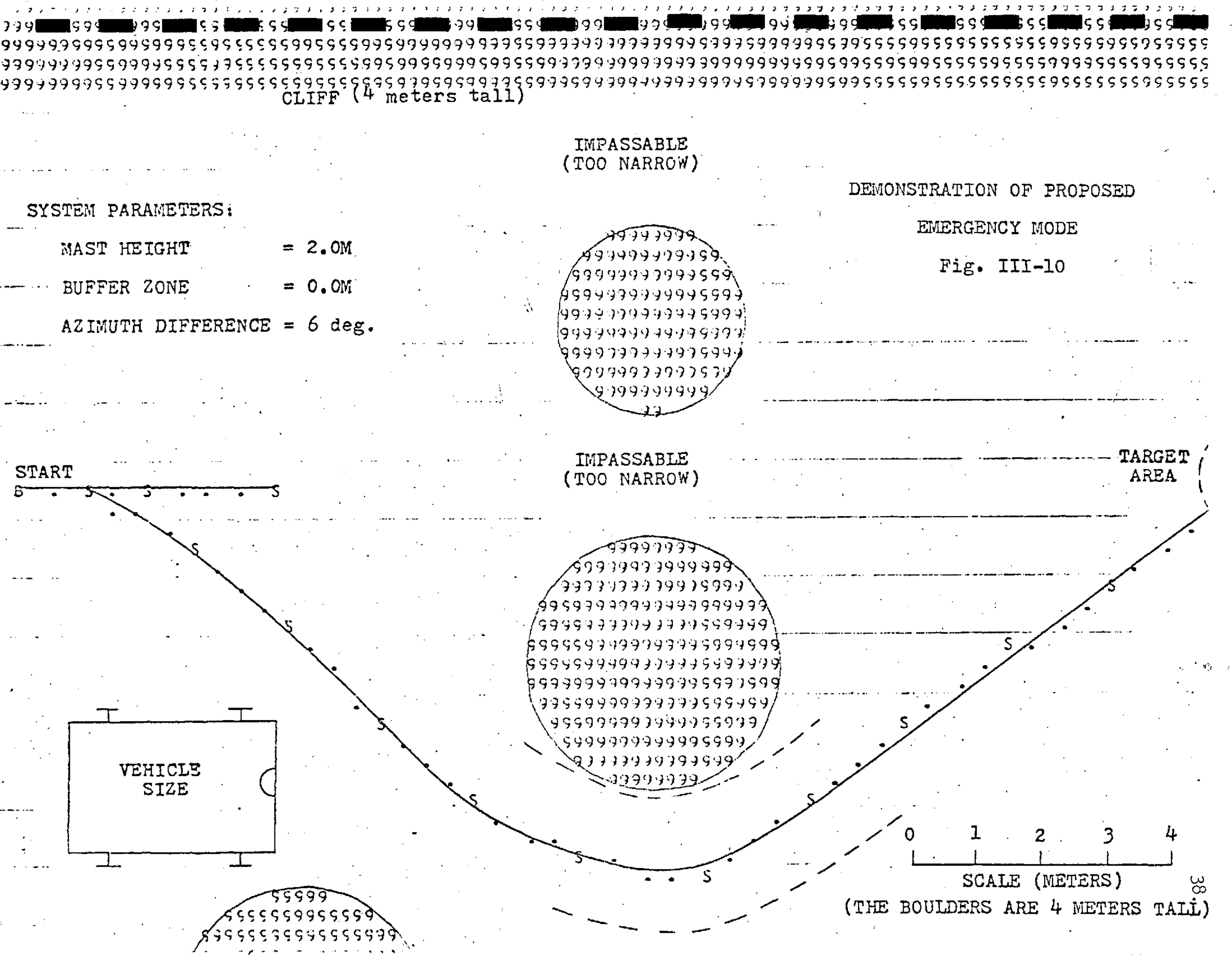
The analysis of this system has shown that it has the ability to successfully navigate the vehicle over most simple and clearly defined obstacle encounters, but has limited ability on realistic terrains and in the presence of random effects.

The analysis of the effects of three system parameters on system performance has shown the following:

1) The type of terrain and the size of obstacles which are detectable is a function of mast height. With mast heights of one-half or one meter, noise disturbances frequently triggered the emergency mode when no emergency really existed. The two meter mast height is not satisfactory for detecting obstacles smaller than the 2 x 2 meter boulder. A mast height of between one and two meters appears to be the best compromise.

2) The additional obstacle clearance obtained as the desired buffer zone is increased beyond one meter is small. A one-half to one meter buffer is recommended. This specification should produce an actual obstacle clearance of 0.4 to 0.85 meters in most cases.

3) With an azimuth difference of six degrees the vehicle frequently struck the 2/3 x 2/3 meter boulder, even in the absence of noise. Results show that in order for the



DEMONSTRATION OF PROPOSED

EMERGENCY MODE

Fig. III-10

system not to lose sight of the small boulder between scan shots, the azimuth difference must be reduced to three degrees or less.

To increase the system's capability to negotiate realistic terrains the following path selection system modifications are recommended as items for future study.

1) The addition of a dual or multi-beam sensor system incorporating different elevation angles or sensor heights. The purpose of varying the orientation or position of sensor locations would be to divorce the function of detecting large positive obstacles from that of detecting small boulders and craters.
2) The use of nonuniform sensor scanning with the greatest density of scans being taken directly in front of the vehicle. This type of scanning would give the system more information about the critical area directly in front of the vehicle, but would also require a more complex terrain modeling process.
3) The incorporation of an emergency mode which has the ability to remember where a trouble area exists until the vehicle has safely passed the problem.

IV. PERFORMANCE OF A SHORT RANGE SYSTEM

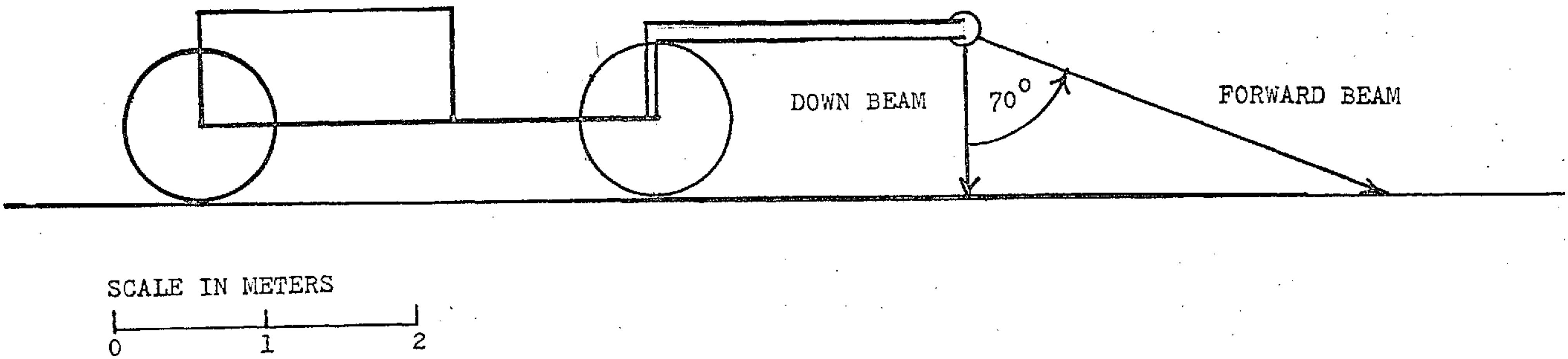
The following discussion describes a computer simulation analysis of a short range path selection system. By the term "short range" it is to be understood that the system's sensors are constrained to have a maximum range of three meters, and can only make range measurements with reasonable accuracy up to this distance. The thrust of this investigation is purely conceptual, aimed at examining the question of whether successful navigation to a distant target can be done effectively based upon range-azimuth data of a limited nature. The sensor model and mounting configuration that were simulated in this analysis should properly be thought of as a method of gathering terrain modeling information at a distance of one to two meters in front of the vehicle and not as a specific hardware design.

A. System Description

1. Sensors and Sensing Configuration

The sensors used in the simulations are ideal beam-type range finders that have a maximum range of three meters and a zero beam width. It is assumed that a measurement with this type of sensor can be made instantaneously. Figure IV-1 shows the sensing configuration that was used in the simulation. Two of the beam type sensors are mounted at the end of an arm attached to the vehicle as shown. The "down beam" makes a range measurement that is used for terrain modeling purposes while the forward beam measurement is used to protect the arm from colliding with a terrain feature.

It is assumed that the arm can be retracted to a length of one meter if necessary. The forward beam range measurement is used to trigger this retraction and to detect the presence of positive obstacles. To compensate



SENSING CONFIGURATION (SIDE VIEW)

Fig. IV-1

for random tilts of the vehicle resulting in inadvertent retractions of the arm, the forward beam is gimballed as a function of the change in the down beam range measurement. This generally insures that the range measured by this beam is at least a meter and a half unless a terrain feature is encountered.

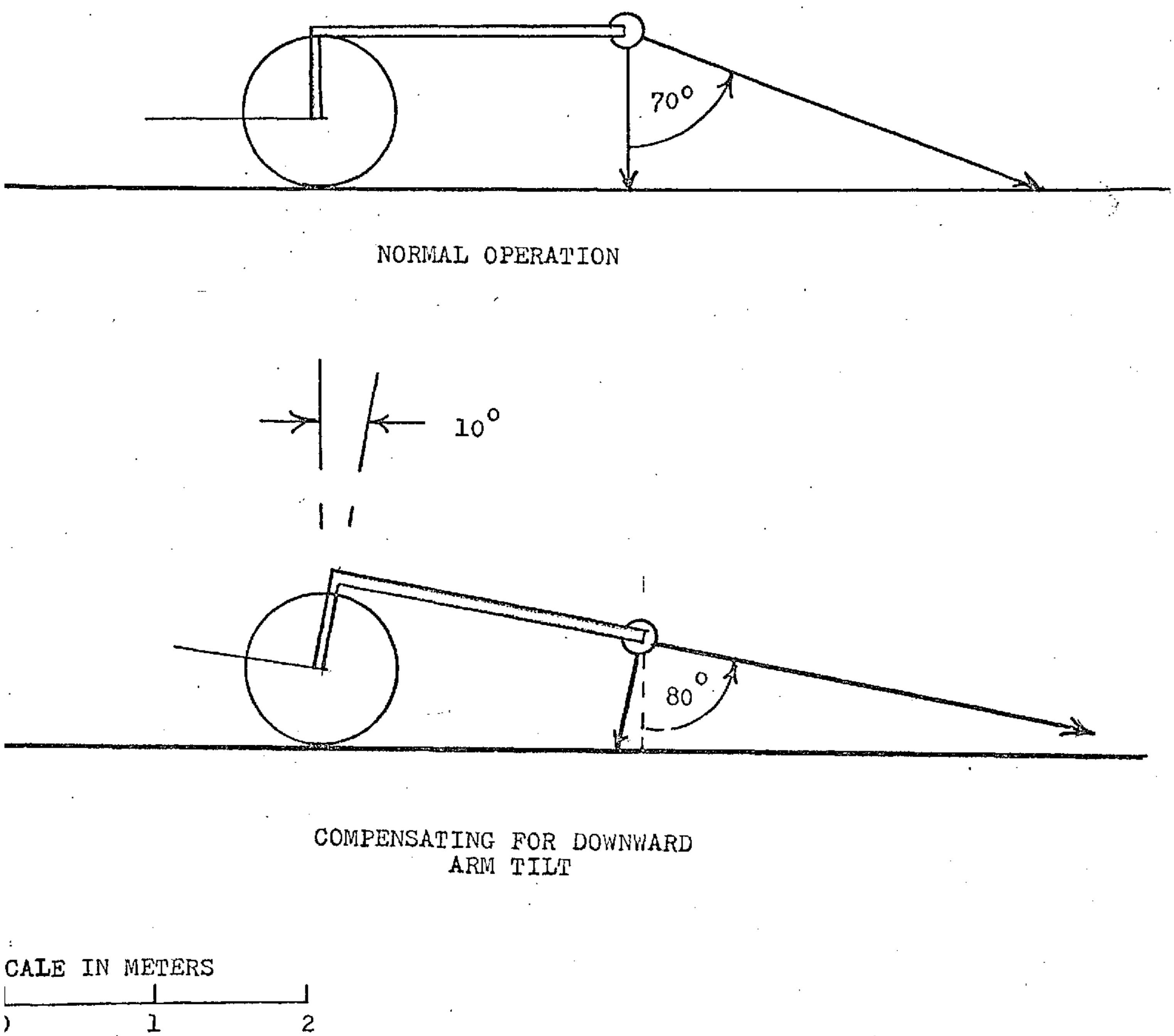
For example, in normal operation the angle of the forward beam is 70° relative to the local normal. However if the arm is tilted downward due to a terrain irregularity the forward beam is gimballed upward by an equal amount (see Fig. IV-2). This operation is assumed to be ideal and the effects of noise are neglected.

During scanning operation the arm is rotated from left to right through a 180° traverse and every six degrees measurements are made with both beams. Figure IV-3 shows a top view of this scheme. It is assumed that the speed of this operation relative to the vehicle's speed allows the change in the vehicle's position during this operation to be neglected and the operation to be repeated at every half meter advance. Because the arm is mechanically operated this assumption is not realistic.

Upon completion of a scan, the stored forward and down beam range information is passed to the terrain modeler for processing.

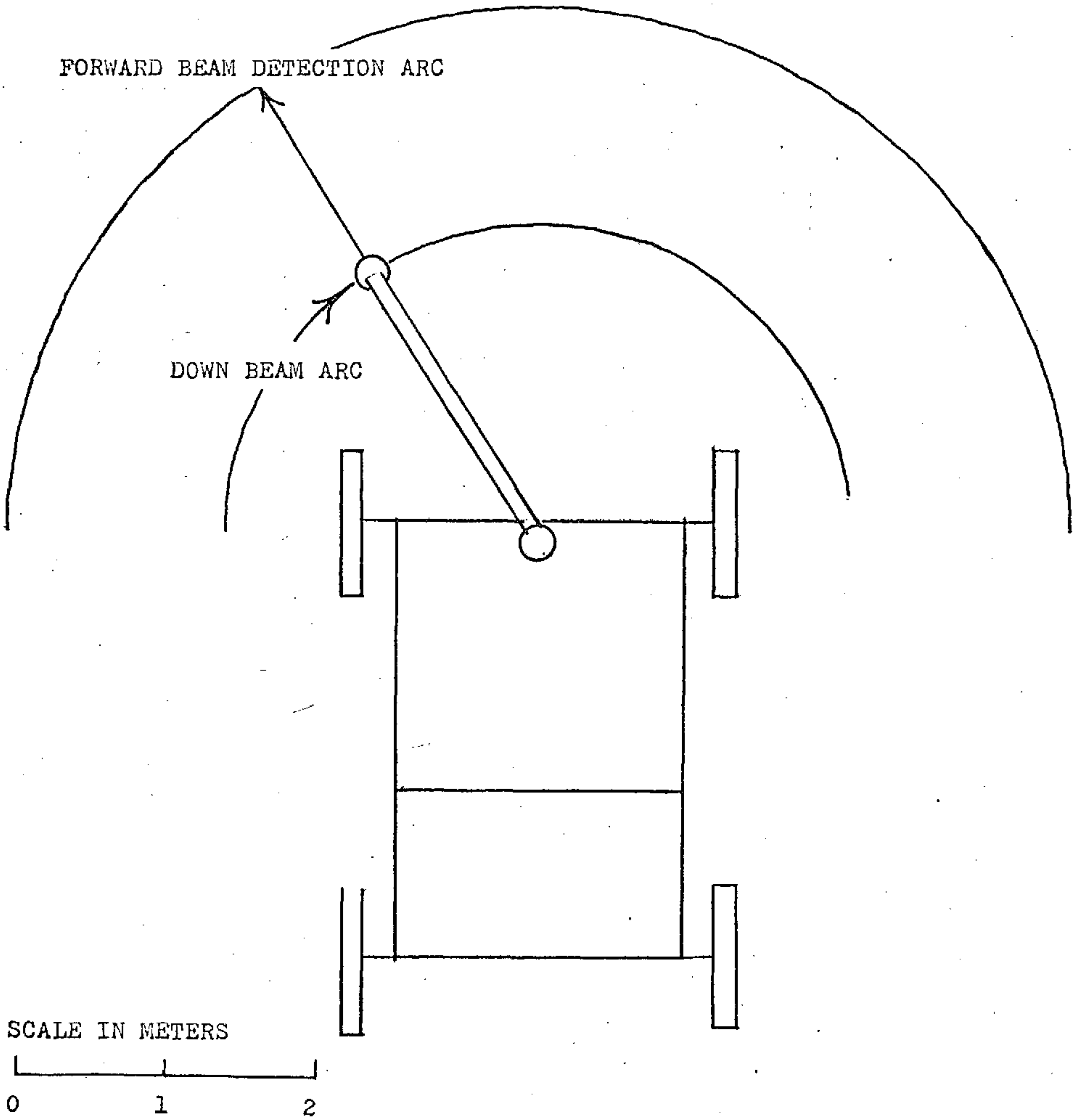
2. Terrain Modeler

The terrain modeler simulates an on-board processor that converts the range-azimuth data provided by the scanning operation into a form amenable to path selection decisions. Down beam information is processed by a slope modeler that converts each range measurement to a slope by assuming a linear slope from the vehicle's position to the beam's impingement point as shown in Fig. IV-4. Measurements of the vehicle's pitch and roll attitudes at the time the scan was performed are used in the



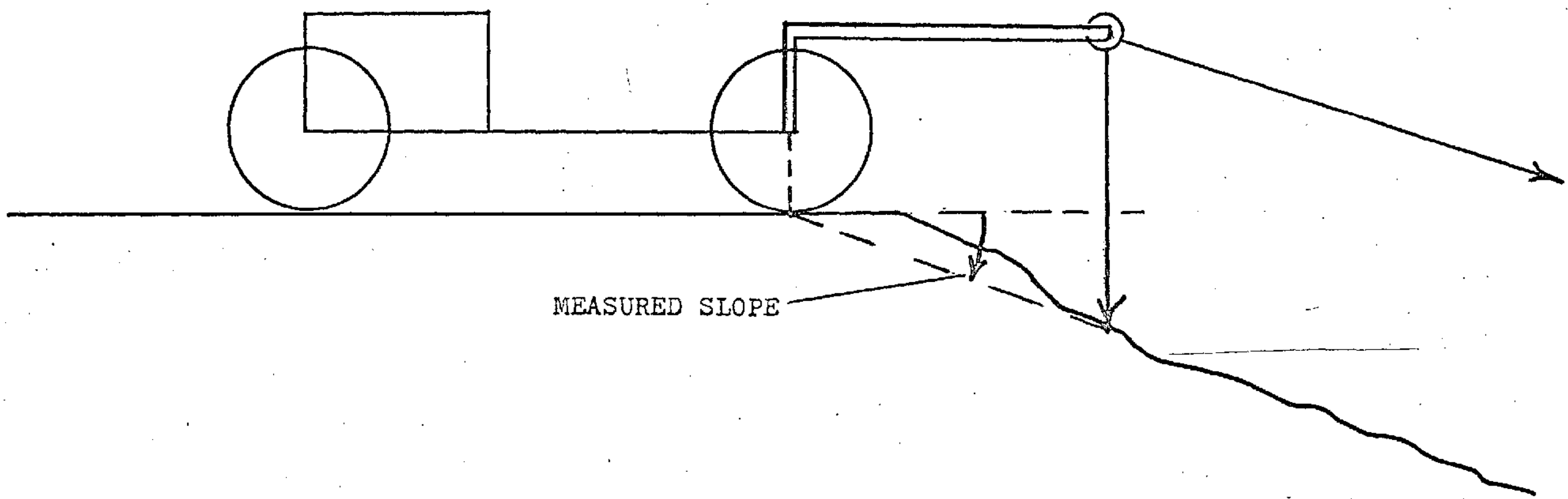
FORWARD BEAM GIMBALLING OPERATION

Fig. IV-2



SENSING CONFIGURATION (TOP VIEW)

Fig. IV-3



SLOPE MEASUREMENT

Fig. IV-4

calculation of this slope to improve its accuracy. The modeler converts the resultant slopes to a go/no-go array by comparing the absolute value of each of the slopes to a 20° threshold. Exceeding this threshold is termed a no-go condition.

Forward beam information is processed into a one-zero array by comparing each measurement to a 1.5 meter threshold. A measurement less than 1.5 meters is assigned a zero. Both the go/no-go and one-zero arrays are then passed to the path selection algorithm for processing.

3. Path Selection Algorithm

The algorithm begins processing by analyzing the forward beam range information provided by the terrain modeler. If any of these measurements are less than 1.5 meters, indicated by a zero in the one-zero array, the algorithm assumes that a substantial change in slope is occurring due to approaching or leaving a hillside. The sensor arm is retracted to a one meter length to obtain a safe clearance during this maneuver and is held in the retracted mode for three successive scans before being re-extended. If the arm is already in the retracted mode and a forward beam range measurement is less than 1.5 meters the algorithm assumes the measurement indicates a no-go condition. In this fashion a forward beam go/no-go array is assembled.

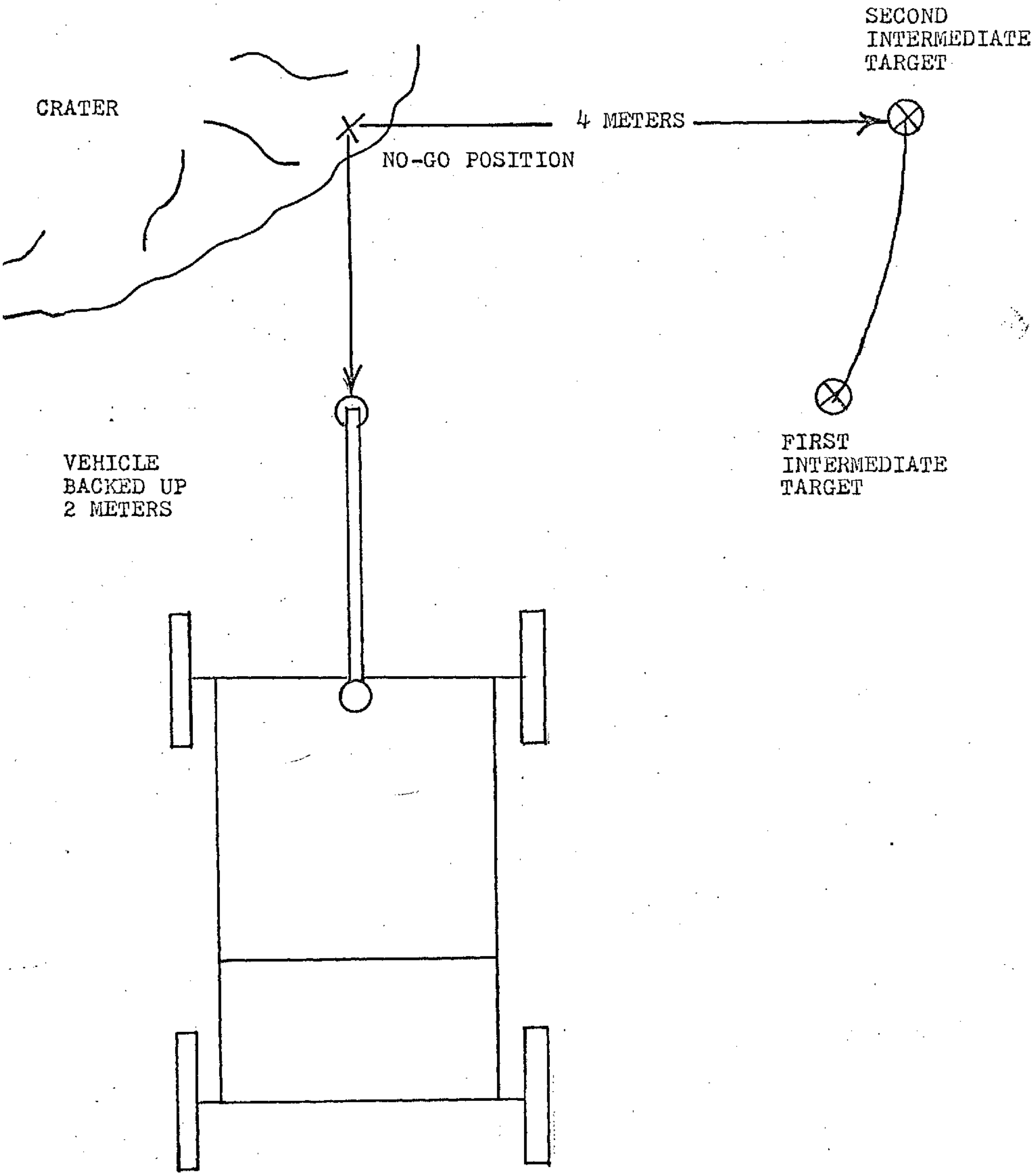
Both forward and down beam go/no-go arrays are then scanned to determine if a no-go condition exists. If the area in front of the vehicle is clear the azimuth from the vehicle's current position to target is computed and assigned as the next steering command. If a no-go condition exists, the system goes into the avoidance mode and the vehicle is backed up two meters on a straight line to obtain room to maneuver. The algorithm then computes a path around the righ-most or left-most no-go condition by assigning two intermediate targets on a four meter radial arc centered on the no-go condition as shown in Fig. IV-5. The choice of moving to the right or left is dictated by choosing the shortest avoidance path.

In summary, this short range system probes cautiously forward obtaining terrain information concerning the vehicle's immediate path. Once an obstacle is detected the vehicle is backed up a short distance on a straight line to obtain room to maneuver. From the information obtained when the detection of the obstacle occurred, the path selection system estimates the obstacle's size and computes a "safe" path around the right or left edge. The shortest detour from the intended line of travel is chosen as the avoidance path.

B. Simulation Procedure

1. Test Procedure

The computer analysis of the short range system generally followed the procedure outlined in Section II of this report. This analysis began with a sequence of simulations involving a single boulder or crater encounter on a flat base terrain. The system's deterministic performance was examined as well as its performance in the presence of attitude, range and slope measurement noise. Attitude noise was simulated by adding filtered white noise with a maximum deviation of 10° to the vehicle's in-path and cross-path slopes as it moved across the test terrain. Range and slope measurement noise were simulated by adding unfiltered white noise to these measurements during every scanning operation. Appropriate noise levels for range and slope measurement noise were obtained by running several simulations using each random effect alone and specifying different maximum deviations for the distribution of the noise. Maximum deviations of 0.1 meters and 5° where chosen to simulate



AVOIDANCE MANEUVER

Fig. IV-5

these effects and the system's noisy performance was simulated by using all of the random effects together.

The flat plain, single obstacle encounter simulations provided information about the effect of each type of noise on the system's obstacle avoidance performance. In addition, successful performance on this simple test terrain served as a justification for proceeding to more difficult situations.

The short range system's ability to avoid a single boulder or crater in a non-zero slope setting was examined by simulations involving a single obstacle encounter on the gently rolling and rolling incline test terrains shown in Figs. II-2 and II-3. Simulations without an obstacle were run for both deterministic and noisy performance cases to determine the vehicle's path to target and to serve as baselines when evaluating the system's obstacle avoidance behavior. The boulder or crater was placed on this path in subsequent simulations at locations where the local slopes made detection difficult.

After examining the short range system's ability to negotiate about a single obstacle in a variety of slope settings and in the presence of random effects, attention was turned to multi-obstacle encounters. The present evaluation of this system was terminated by simulating the system's noisy performance in traversing the boulder-crater field shown in Fig. II-6.

2. Performance Evaluation

The short range system's performance in each simulation was "graded" by assigning to it a figure of merit computed by (see Ref. 1):

$$\text{Figure of Merit} = \sum_{i=1}^{5} W_i F_i$$

where:

F_i = a zero (worst case) to unity (best case) index of a given performance characteristic.

W_i = the weight of the corresponding index.

The weights were chosen so that the figure of merit would vary from zero to a maximum of unity for ideal performance. The following indices were used:

a) Path Length

Excessively long, wandering paths to target were penalized by using an index of the form:

$$F_1 = \frac{D_m}{D_e + D_m}$$

where D_m is the distance between the starting position and the target, and $D_e + D_m$ is the length of the path taken by the system.

b) Battery Usage

Selecting paths containing steep slopes, thereby forcing the vehicle to rely on its batteries, was penalized by using an index of the form:

$$F_2 = \frac{T - T_b}{T}$$

where T is the time taken to reach the target and T_b is the amount of time the batteries were used.

c) Traverse Time

To penalize slow, inefficient performance the following index was used:

$$F_3 = \frac{T_m}{T_e + T_m}$$

where T_m is the minimum time necessary to reach target by travelling on a straight line path from the starting position to the target, and $T_m + T_e$ is the time the system actually took to reach the target.

d) Obstacle Detection

The system's failure to detect the presence of a boulder or crater in a one meter semi-circle immediately in front of the vehicle was counted as an obstacle detection error. Making such errors in the course of a simulation was penalized by an index:

$$F_4 = \frac{N_e}{1 + N_e}$$

where T is the total number of detection errors the system committed during the simulation.

e) Path Safety

A measure of the safety of the chosen path was obtained by first assigning buffer distances of 0.5 meters for boulders and 1.0 meters for craters. If during the simulation the distance between the vehicle and the obstacle grew less than the specified buffer distance, a penalty of 1/2 was assigned. If the vehicle struck the obstacle a penalty of one was assigned. Performance was measured by:

$$F_5 = \frac{1}{1 + P}$$

where P is the sum of the assigned penalties.

The path length, battery usage, and traverse time indices were each assigned weights of 0.10. The obstacle detection, and path safety indices were assigned weights of 0.20 and 0.50, respectively.

In addition to the figure of merit, the vehicle's closest approach to the obstacle before detection and the minimum clearance maintained as the vehicle circled the edge of the obstacle were recorded as indicators of performance in each simulation.

C. Simulation Results

1. Case I: Single Boulder Encounter on a Flat Base Terrain

This first sequence of simulations involved an encounter with a 2/3 meter high, drum model boulder on a flat base terrain. The results are summarized in Tables IV-1 and IV-2.

As Table IV-2 indicates the results for all simulations except Test 6 were identical. In the tests exhibiting similar results the boulder was initially detected by the forward beam when the fully extended arm was slightly less than 1.5 meters from the boulder. This first detection caused the arm to be retracted to a one meter length and the vehicle continued to move forward. A second detection by the forward beam occurred when the retracted arm was roughly 0.67 meters from the boulder. The path selection algorithm now recognized the existence of an obstacle in the vehicle's path and initiated a two meter backup. The vehicle was then directed to circle the estimated location of the boulder's right edge. A typical vehicle path map for these simulations is shown in Fig. IV-6.

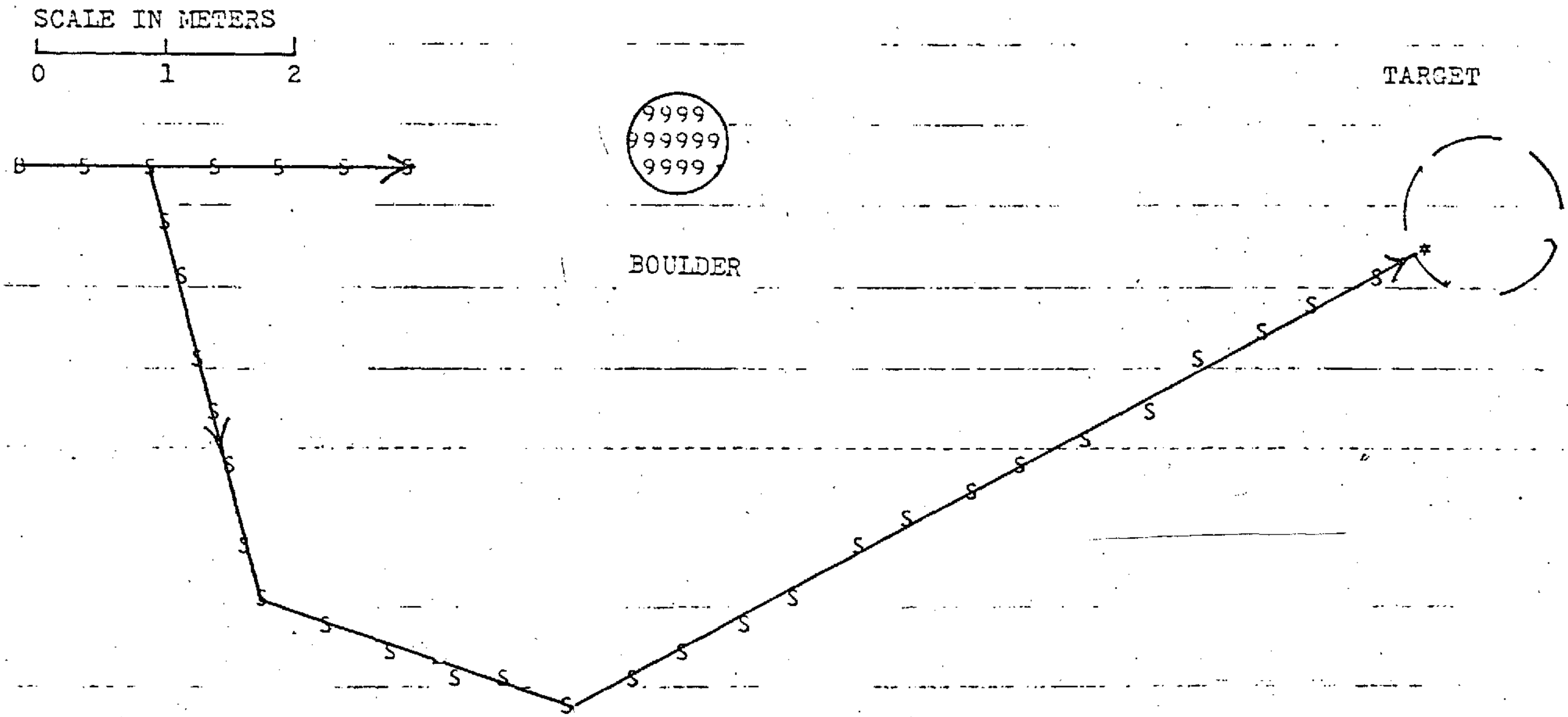
The similarity of the results for these tests, though in each case a different random effect is being employed, is explained by noting the effect of each type of noise on the forward beam range measurement. Detection before the boulder is under the arm depends solely upon the magnitude of this measurement. Clearly this measurement is independent of slope measurement noise. Attitude noise is compensated for by gimballing the forward beam as a function of the down beam range measure-

TABLE IV-1. SIMULATION SEQUENCE FOR CASE I

Test Number	Noise Type Used	Mean	Maximum Diviation
1	None	-	-
2	Attitude	0.	10.0^{o}
3	Slope Measurement	0.	5.0^{o}
4	Slope Measurement	0.	10.0^{o}
5	Range Measurement	0.	0.1 meter
6	Range Measurement	0.	0.5 meter
7	Attitude	0.	10.0^{o}
	Slope Measurement	0.	5.0^{o}
	Range Measurement	0.	0.1 meter

TABLE IV-2. PERFORMANCE RESULTS FOR CASE I

Item	Test Numbers 1	2	3	4	5	6	7
Closest Approach Distance Before Detection (meters)	1.67	1.67	1.67	1.67	1.67	0.67	1.67
Minimum Clearance While Circling Edge (meters)	2.20	2.20	2.20	2.20	2.20	2.60	2.20
Selected Path Length (meters)	18.50	18.50	18.50	18.50	18.50	19.00	18.50
Battery Usage Time (seconds)	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Total Travel Time (seconds)	18.50	18.50	18.50	18.50	18.50	19.00	18.50
Number of Buffer Penalties	0	0	0	0	0	0	0
Number of Detection Errors	0	0	0	0	0	1	0
Number of Collisions With an Obstacle	0	0	0	0	0	0	0
Figure of Merit	0.907	0.907	0.907	0.907	0.907	0.806	0.907



CASE I: TYPICAL OUTPUT FOR TESTS 1, 2, 3, 4, 5, 7.

Fig. IV-6

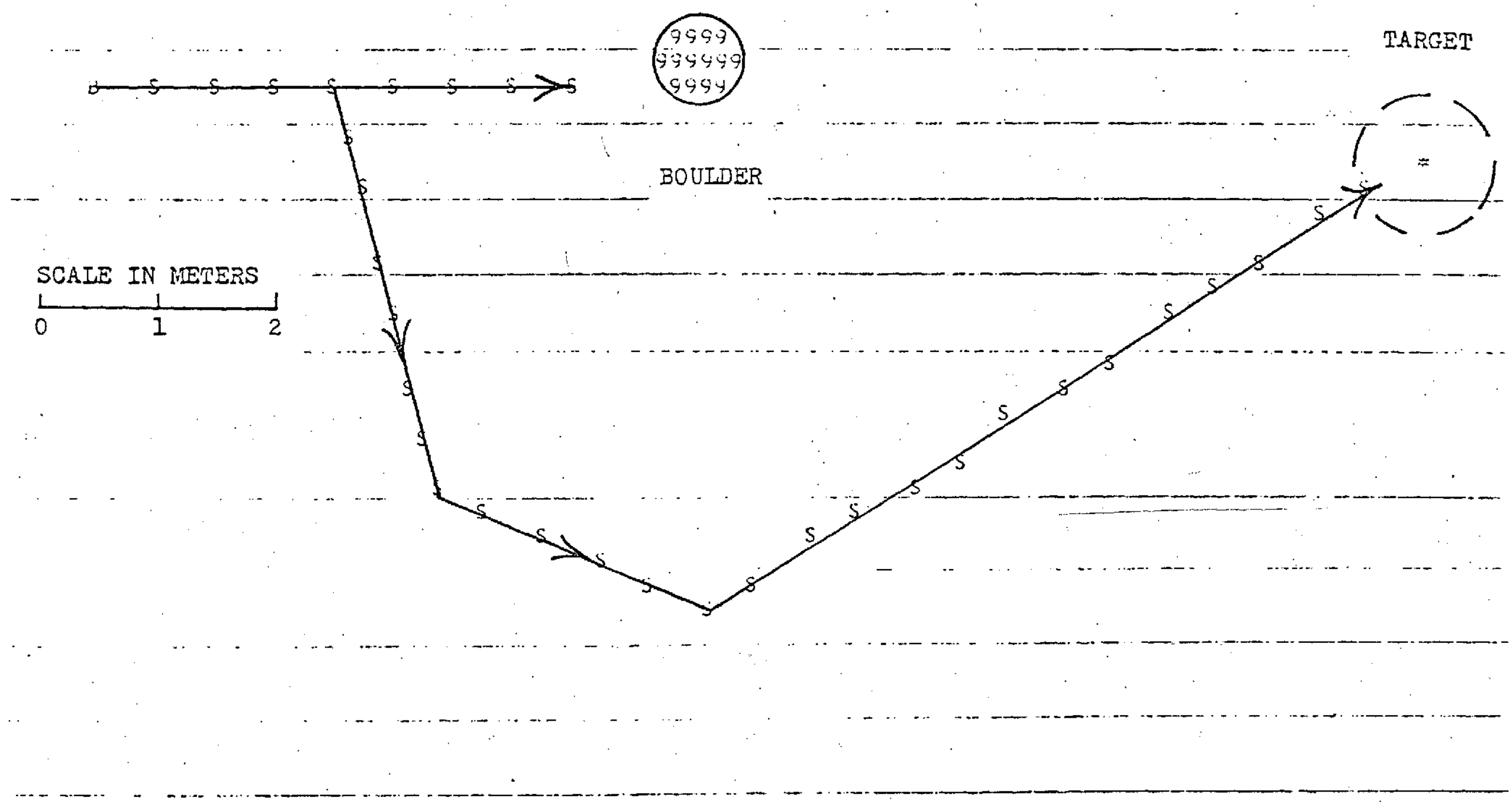
ment and this seems to have worked successfully in this case. Range measurement noise with a maximum deviation of 0.1 meters causes only negligible corruption of the range measurements and a small amount of spurious gimballing of the forward beam. Apparently this noise level can be tolerated without degrading the system's performance. Test 7 indicates that the system can perform adequately in the presence of all three of these noise effects for the noise levels specified in this simulation.

In Test 6, where range measurement noise with a maximum deviation of 0.5 meters is being used, the simulation output and vehicle path map shown in Fig. IV-7 indicate the results of this test are the same as the other tests until the first detection of the boulder occurs. At this point in the simulation the noise in the down beam range measurement becomes strong enough to cause the forward beam to be gimballed over the approaching boulder. The system finally detects the boulder with a down beam slope measurement when the boulder is 0.67 meters from the front of the vehicle. A detection penalty is assigned for failing to detect at a range greater than one meter.

2. Case II: Single Crater Encounter on a Flat Base Terrain

The same sequence of simulations shown in Table IV-1 was repeated for encounters involving a single crater on a flat base terrain. A spherically shaped crater, one meter deep and three meters in diameter, was used. The results of these simulations are summarized in Table IV-3.

In Test 1 the system's deterministic behavior was examined and the vehicle path map for this simulation shown in Fig. IV-8 indicates a performance comparable to the successful boulder cases. The system detects the crater at a distance of 1.5 meters in front of the vehicle, backs up

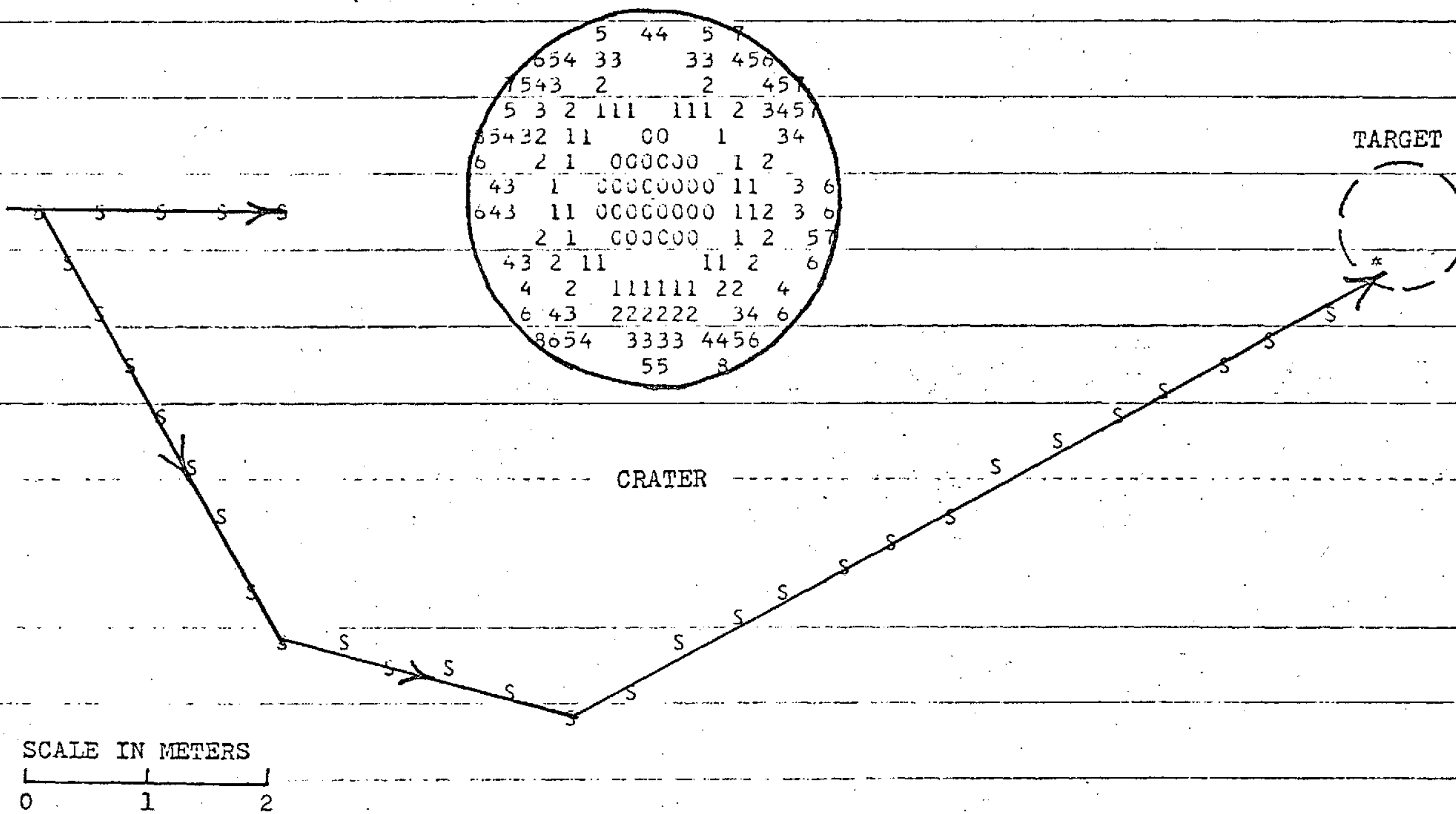


CASE I: TEST 6 (RANGE MEASUREMENT NOISE)

Fig. IV-7

TABLE IV-3. PERFORMANCE RESULTS FOR CASE II

Item	Test Numbers						
	1	2	3	4	5	6	7
Closest Approach Distance Before Detection (meters)	1.50	2.00	1.00	1.00	1.50	1.50	1.50
Minimum Clearance While Circling Edge (meters)	0.828	0.934	1.11	1.11	0.909	1.18	1.13
Selected Path Length (meters)	18.00	23.50	18.50	18.00	18.00	19.00	24.50
Battery Usage Time (seconds)	2.00	4.00	2.00	2.00	2.00	2.00	4.00
Total Travel Time (seconds)	18.00	23.50	18.50	18.00	18.00	19.00	24.50
Number of Buffer Penalties	3	1	1	1	2	0	0
Number of Detection Errors	0	0	1	1	0	0	0
Number of Collisions With an Obstacle	0	0	0	0	0	0	0
Figure of Merit	0.611	0.711	0.642	0.643	0.659	0.907	0.879



CASE II: TEST 1 (NO NOISE)

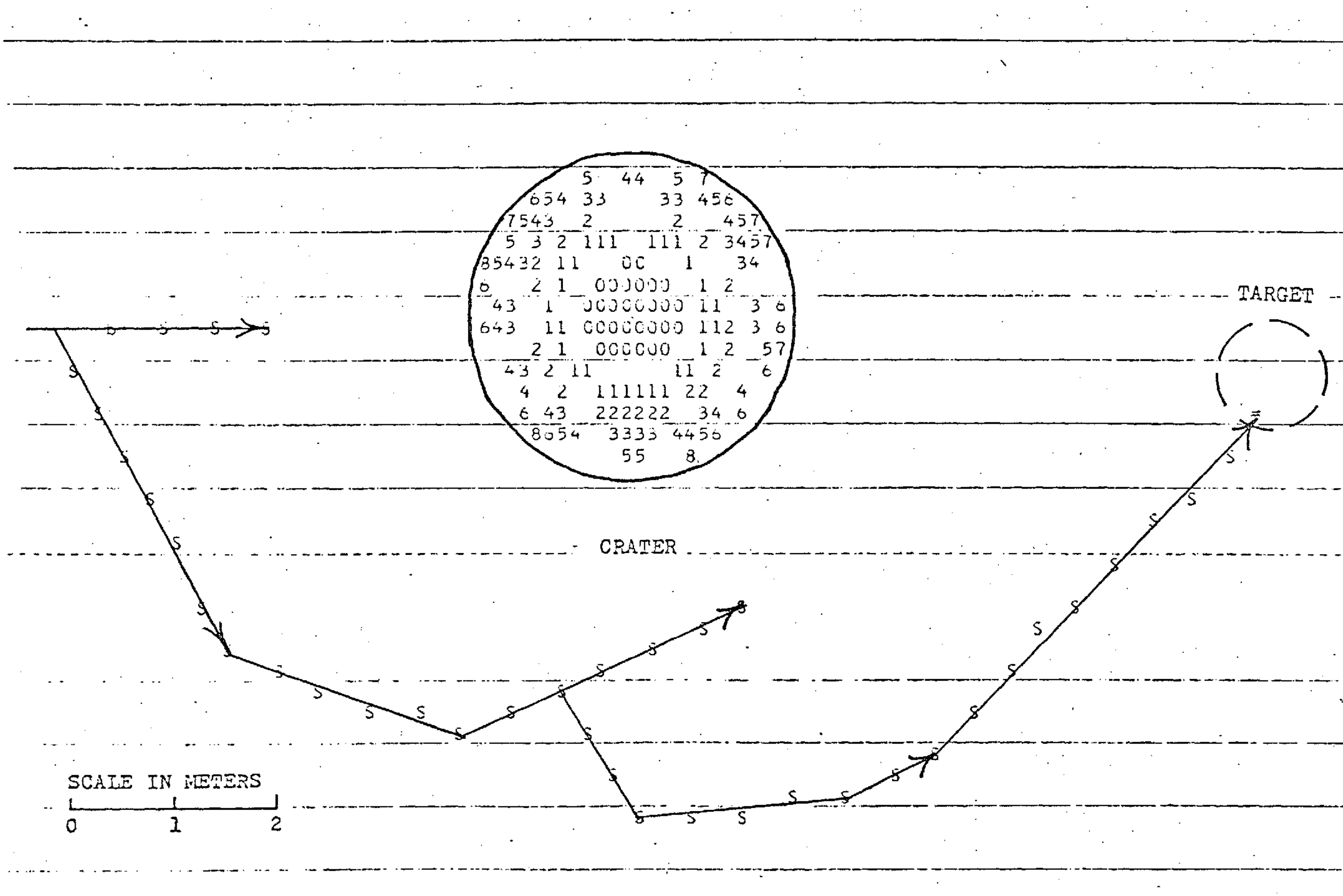
Fig. IV-8

and circles around the obstacle's right edge to target. This performance is awarded a somewhat low figure of merit for passing too close to the edge of the crater during the circling maneuver.

This type of behavior of passing to close to the crater as it slides from view causes the second backup and avoidance maneuver shown in Fig. IV-9, the vehicle path map for Test 2. In this simulation attitude noise is being used and a random tilt forward as the vehicle approaches the crater causes detection to occur sooner than in the deterministic case. The second backup results in a safer path and a higher figure of merit for this simulation.

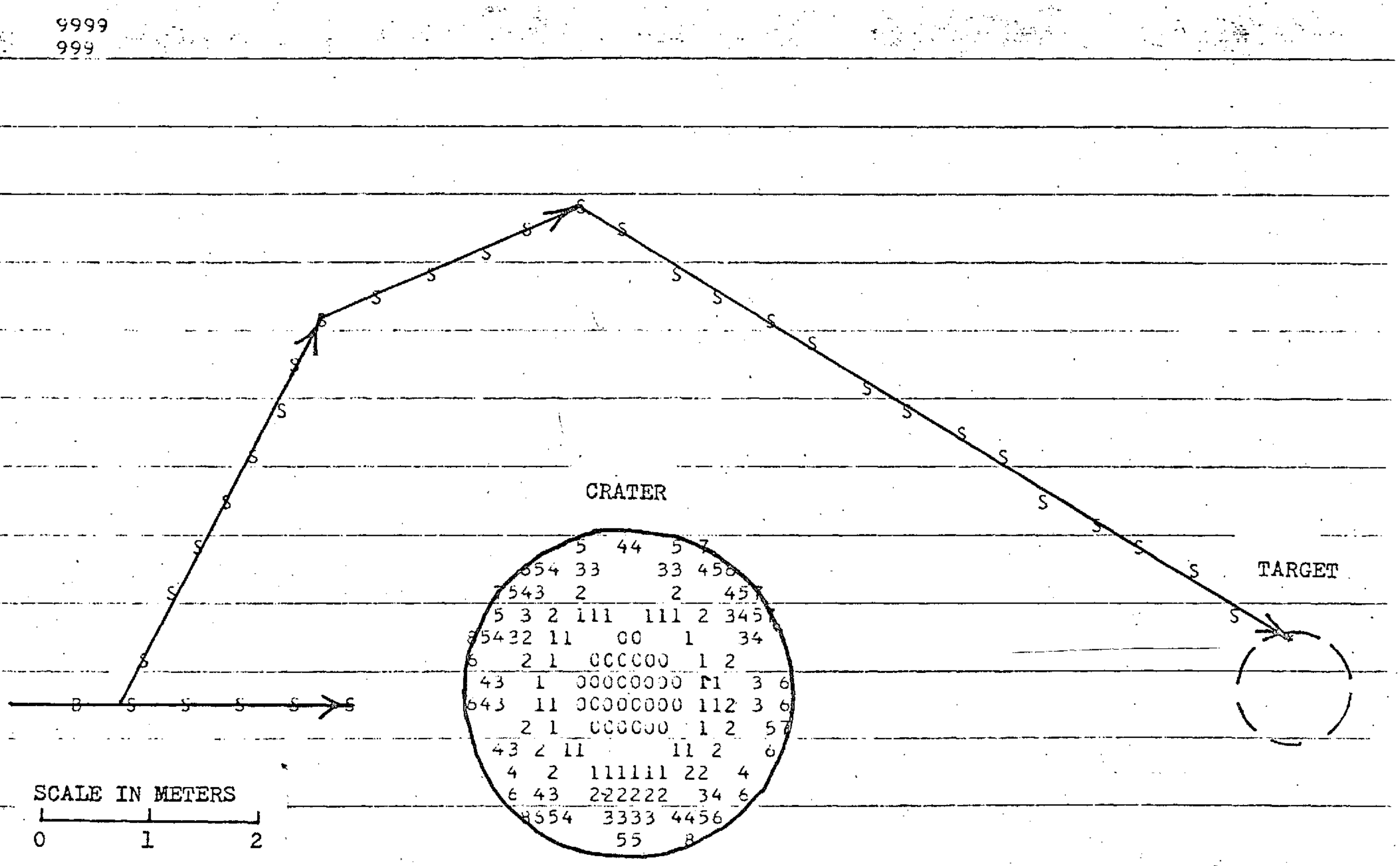
The vehicle path maps for Tests 3 and 4 are shown in Figs. IV-10 and IV-11 respectively. The results of both simulations are quite similar. In both cases the system fails to detect the crater until it is one meter from the front of the vehicle. The noise being used in these simulations corrupts the measurement of the vehicle's orientation that is used in computing a slope from the down beam range measurement. This seems to have masked the presence of the crater in these two simulations. Once the crater is detected a good estimate of its size is obtained and a safe avoidance path is computed. The vehicle moves to the left because the random effects have made the crater appear to lie to the right of the line of travel.

The results of Test 5, where low order range measurement noise is being used, are comparable to the results obtained for the deterministic case as shown by Table IV-3 and a comparison of Figs. IV-8 and IV-12. When the range measurement noise level is increased in Test 6 the detected crater appears to be quite large to the system and the wide avoidance path shown in Fig. IV-13 is taken, resulting in a good figure of merit.



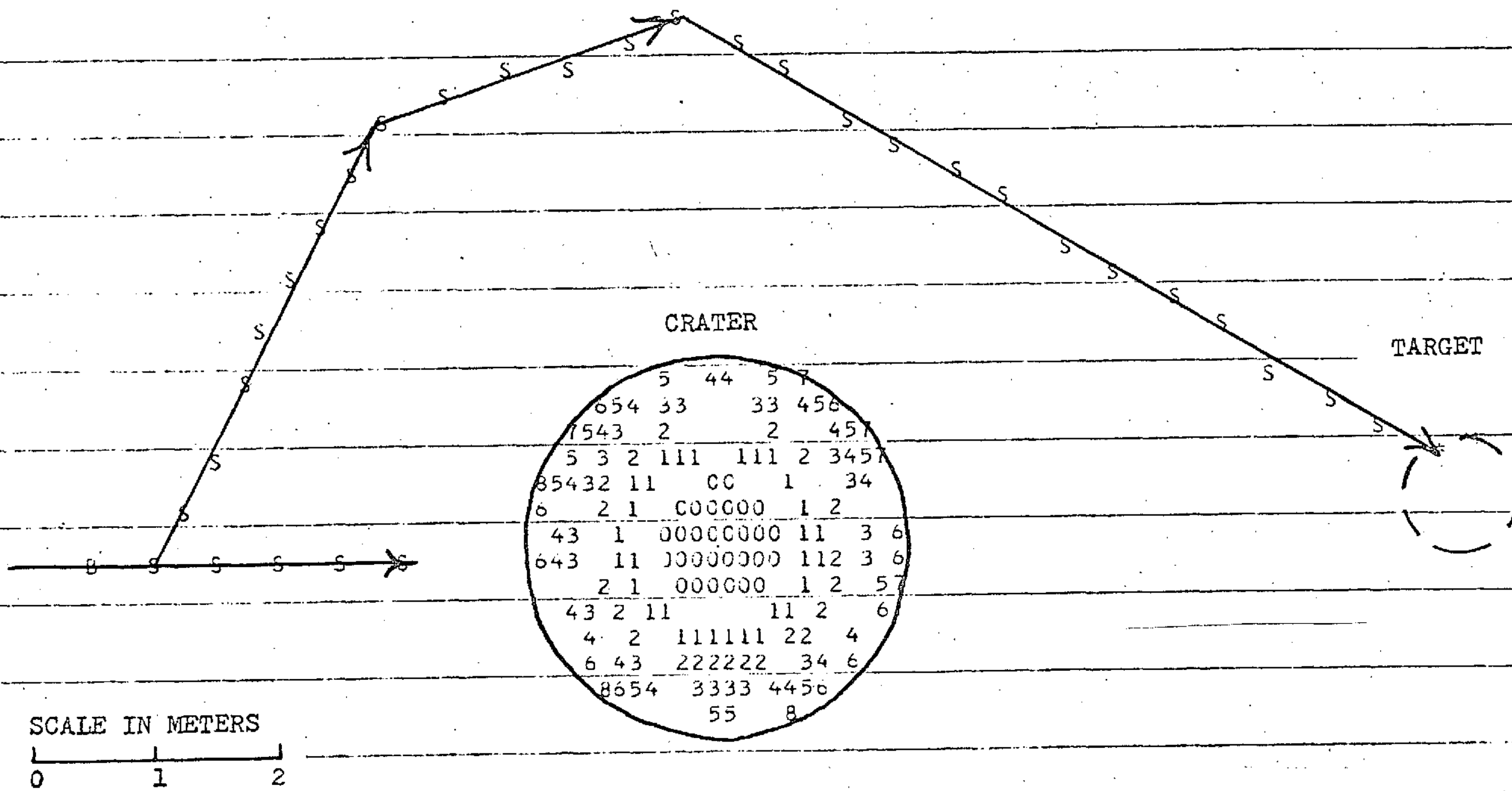
CASE II: TEST 2 (ATTITUDE NOISE)

Fig. IV-9



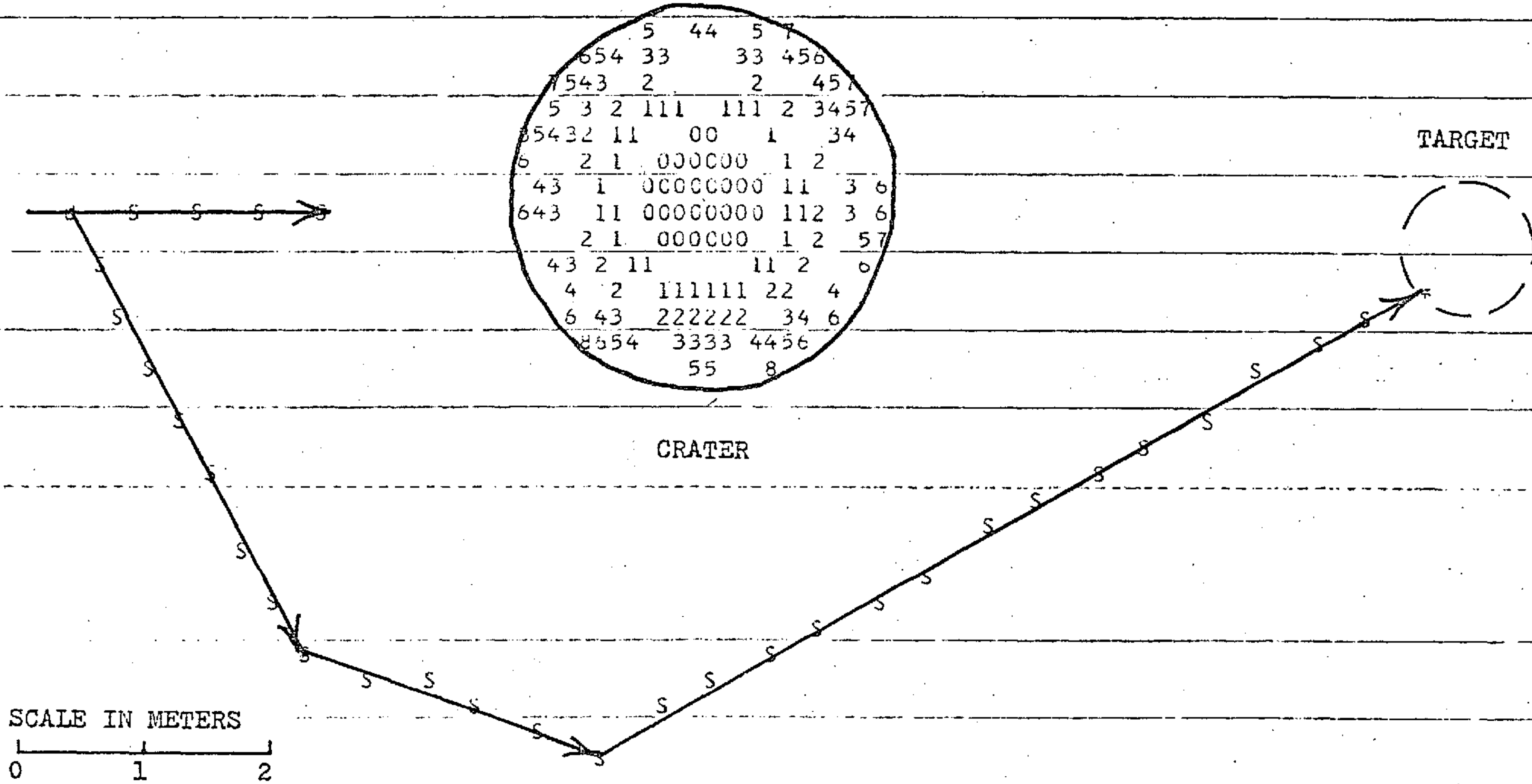
CASE II: TEST 3 (SLOPE MEASUREMENT NOISE)

Fig. IV-10



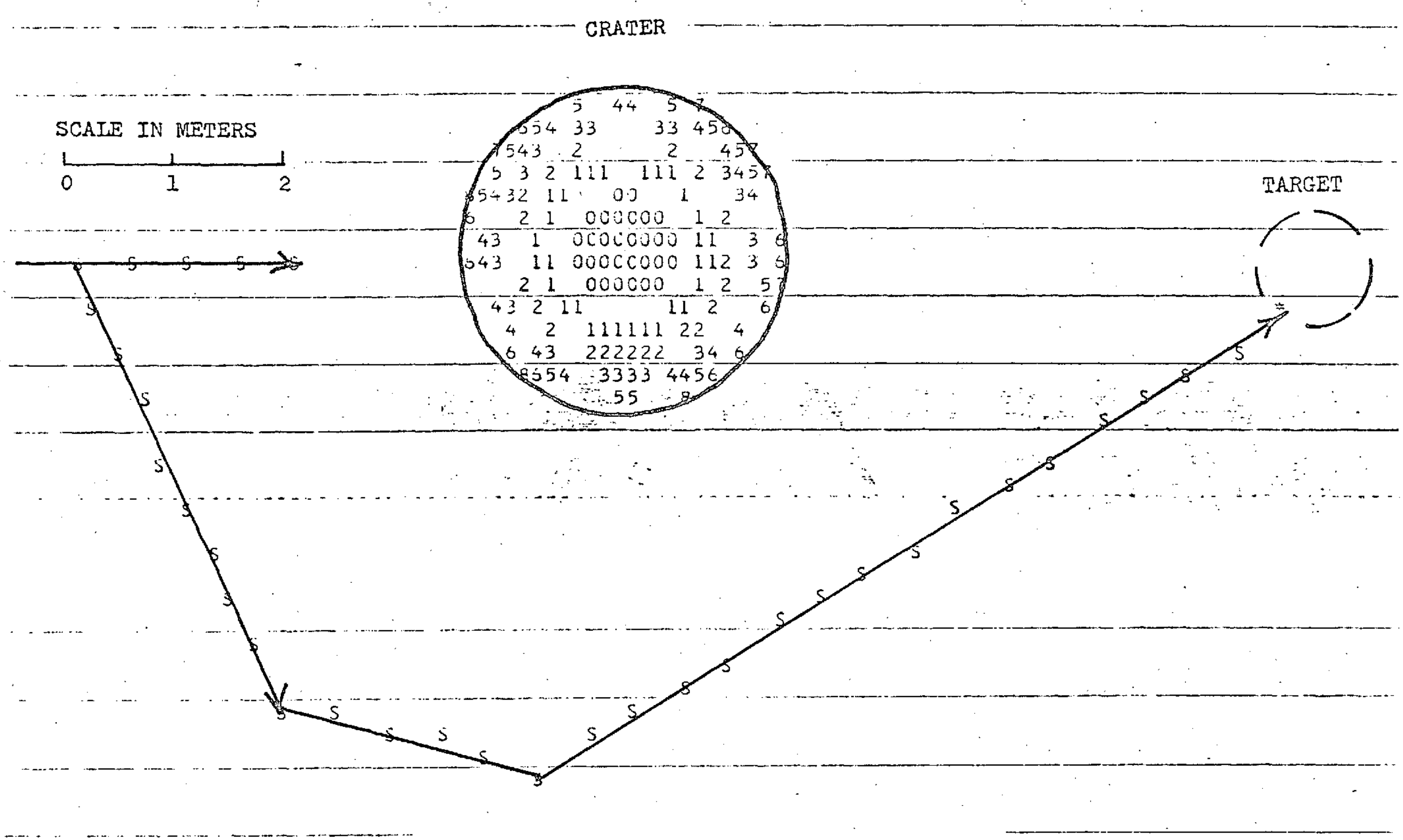
CASE II: TEST 4 (SLOPE MEASUREMENT NOISE)

Fig. IV-11



CASE II: TEST 5 (RANGE MEASUREMENT NOISE)

Fig. IV-12



CASE II: TEST 6 (RANGE MEASUREMENT NOISE)

Fig. IV-13

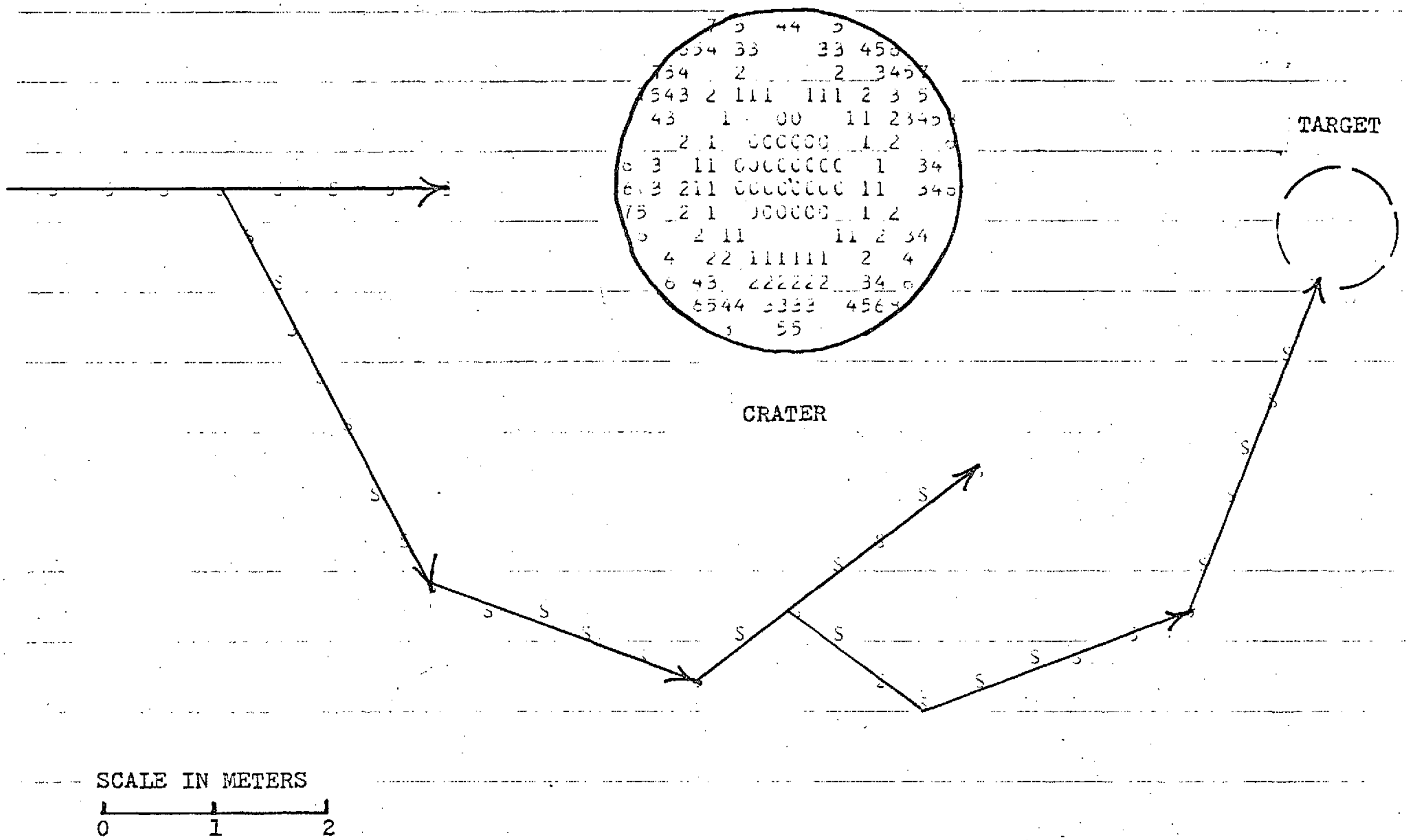
In Test 7 attitude, range and slope measurement noise are used simultaneously at levels indicated in Table IV-1. Acceptable results are obtained as shown by Fig. IV-14 and Table IV-3. In subsequent simulations the system's noisy performance was examined by using all of the random effects simultaneously at the noise levels shown to be appropriate in Test 7 of Case I and II. It is to be understood that these noise types and values are being employed when noise is indicated in the table below.

3. Case III: Single Obstacle Encounters on a Gently Rolling Base Terrain

In this sequence of simulations boulder and crater encounter situations on the gently rolling test terrain shown in Fig. II-2 were used to examine the effects of non-zero in-path and cross-path slopes on the system's performance. Before starting this sequence, baseline simulations without obstacles were run for both deterministic and noisy system performance. In the noisy case it was found that the slope measurement threshold of the slope computed from the down beam range measurement needed to be extended from 20° to 25° to successfully navigate this test terrain. A careful check of the outputs of the simulations used in Case I and II indicated that this new threshold would not have changed the results of these simulations.

After completing the baseline cases the single boulder and crater encounter simulations indicated in Table IV-4 were examined. The results of these simulations are summarized in Table IV-5.

The results of Tests 1 and 2, where no noise is being used, are comparable to results obtained for encounters on a flat base terrain. In both simulations the obstacle is detected about two meters from the



CASE II: TEST 7 (ALL TYPES OF NOISE)

Fig. IV-14

TABLE IV-4. SIMULATION SEQUENCE FOR CASE III

Test Number	Noise	Obstacle	Diameter (meters)	Height or Depth (meters)
1		Boulder	2/3	2/3
2		Crater	3	1
3	X	Boulder	2/3	2/3
4	X	Crater	3	1

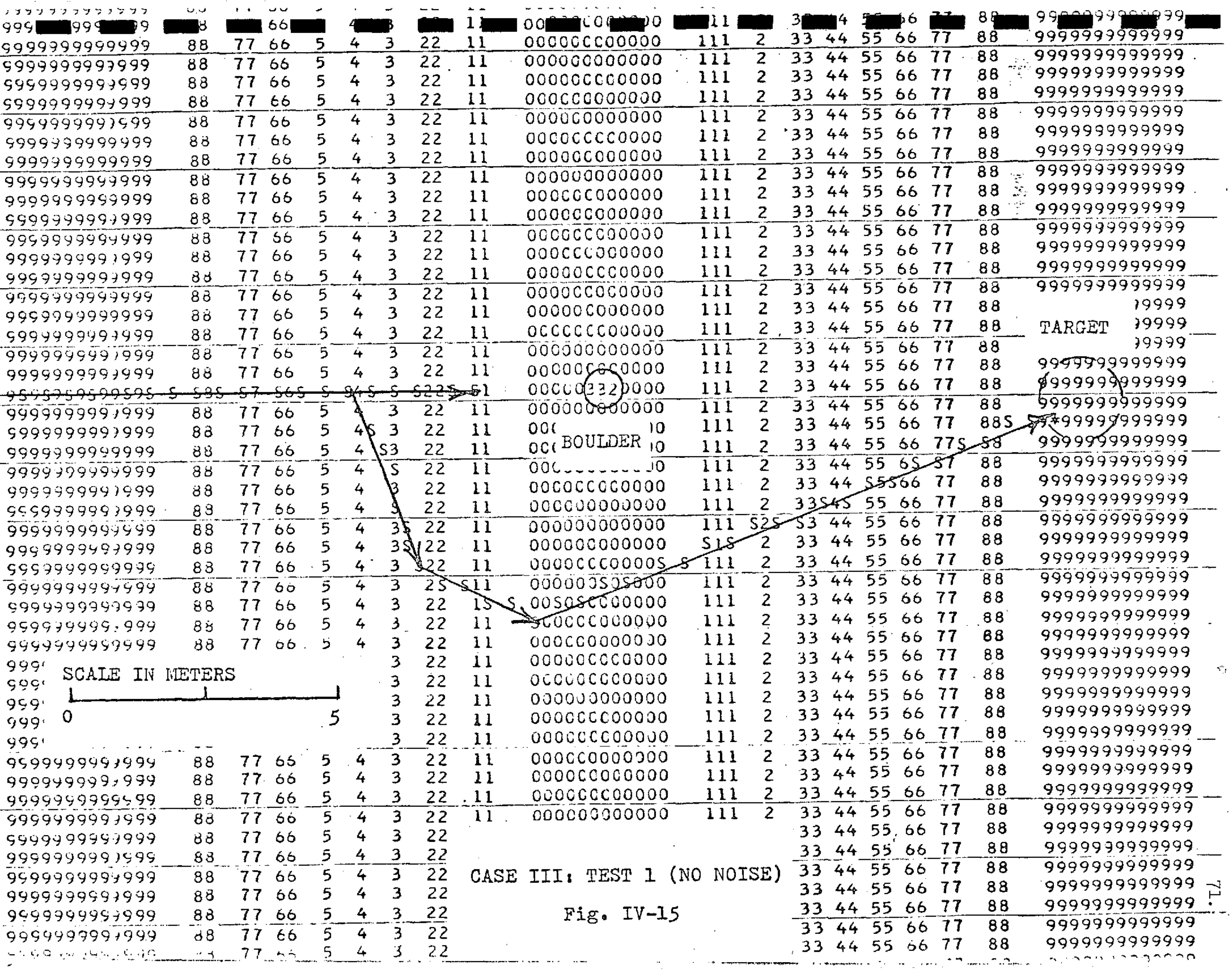
TABLE IV-5. PERFORMANCE RESULTS FOR CASE III

Item	Test Numbers 1	2	3	4
Closest Approach Distance Before Detection (meters)	2.01	1.82	0.724	1.49
Minimum Clearance While Circling Edge (meters)	2.31	1.07	2.28	1.60
Selected Path Length (meters)	32.07	32.09	44.59	36.67
Battery Usage Time (seconds)	13.07	13.09	14.00	16.67
Total Travel Time (seconds)	32.07	32.09	44.59	36.67
Number of Buffer Penalties	0	0	0	0
Number of Detection Errors	0	0	1	0
Number of Collisions With an Obstacle	0	0	0	0
Figure of Merit	0.909	0.909	0.778	0.885

vehicle and a good estimate of its size is obtained. The vehicle path maps for these runs shown in Figs. IV-15 and IV-16 indicate the path selection algorithm has computed a safe avoidance path to target in both simulations. This safe performance results in a high figure of merit in each case.

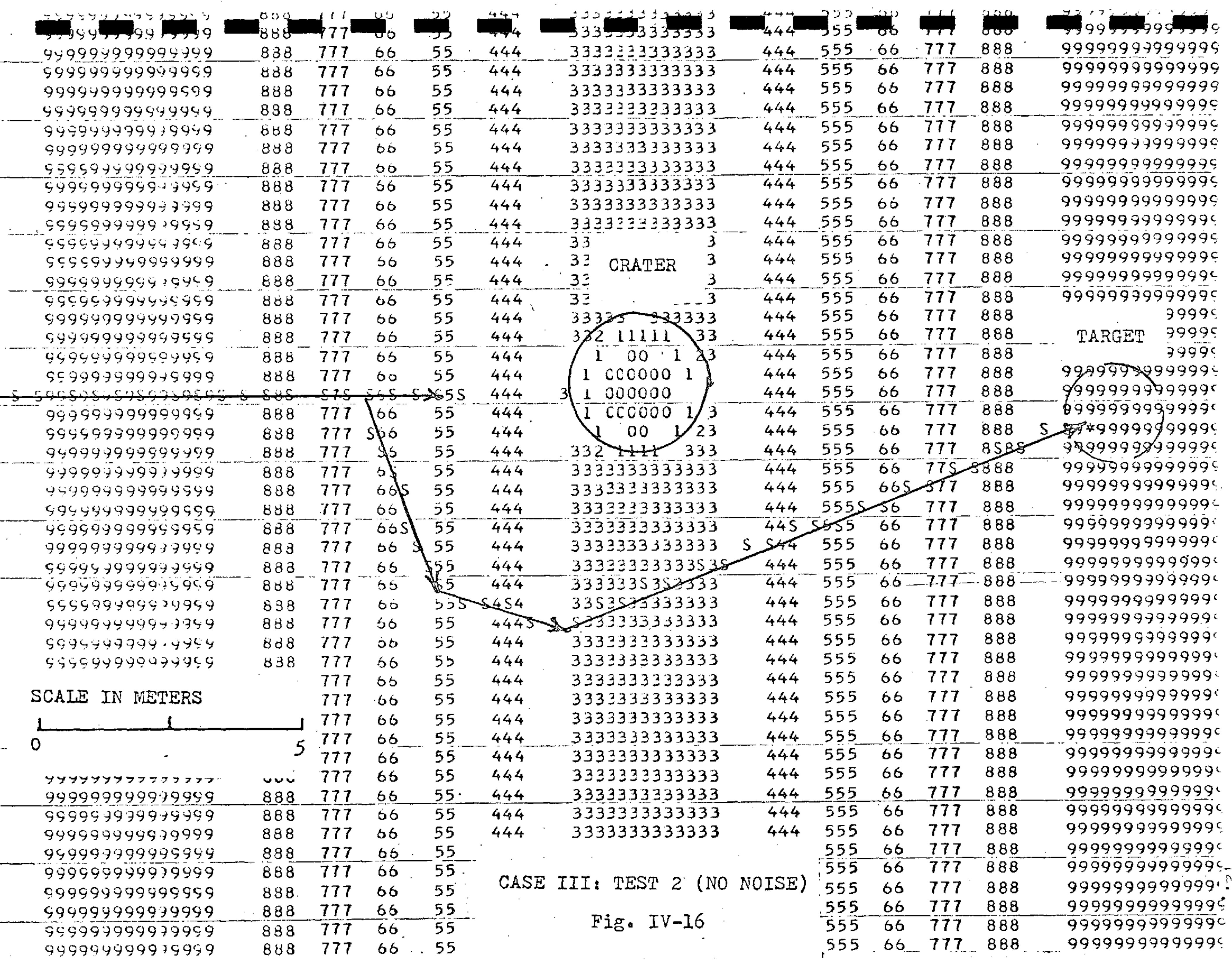
In Fig. IV-17, the vehicle path map for Test 3, the boulder is initially detected at a distance of two meters and the vehicle is directed to circle its left edge. When the vehicle turns toward the final target noise effects cause the up-coming grade to be seen as an obstacle and the system attempts to avoid it by maneuvering around the estimated position of the right edge. While making this maneuver the boulder is encountered a second time but is not detected until it is 0.72 meters from the front of the vehicle. A detection penalty is assigned for failure to detect at a range greater than one meter. At this point, finding its path to the right blocked, the path selection algorithm directs the vehicle back to the point where the grade was detected as an obstacle and now attempts to avoid it by maneuvering left. After a two meter backup the vehicle circles left to target.

In Fig. IV-18, the vehicle path map for Test 4, random effects have masked the presence of the crater in the vehicle's path and have caused a closer approach before detection than in the deterministic case. The vehicle is backed up and starts to circle right when the system is fooled by noise and local slopes that make it appear that the path to the right is blocked. The vehicle is directed back to the point where it first detected the crater and avoidance is attempted by circling to the left. The left edge of the crater is detected forcing a second backup and a deeper swing left around the crater to target.



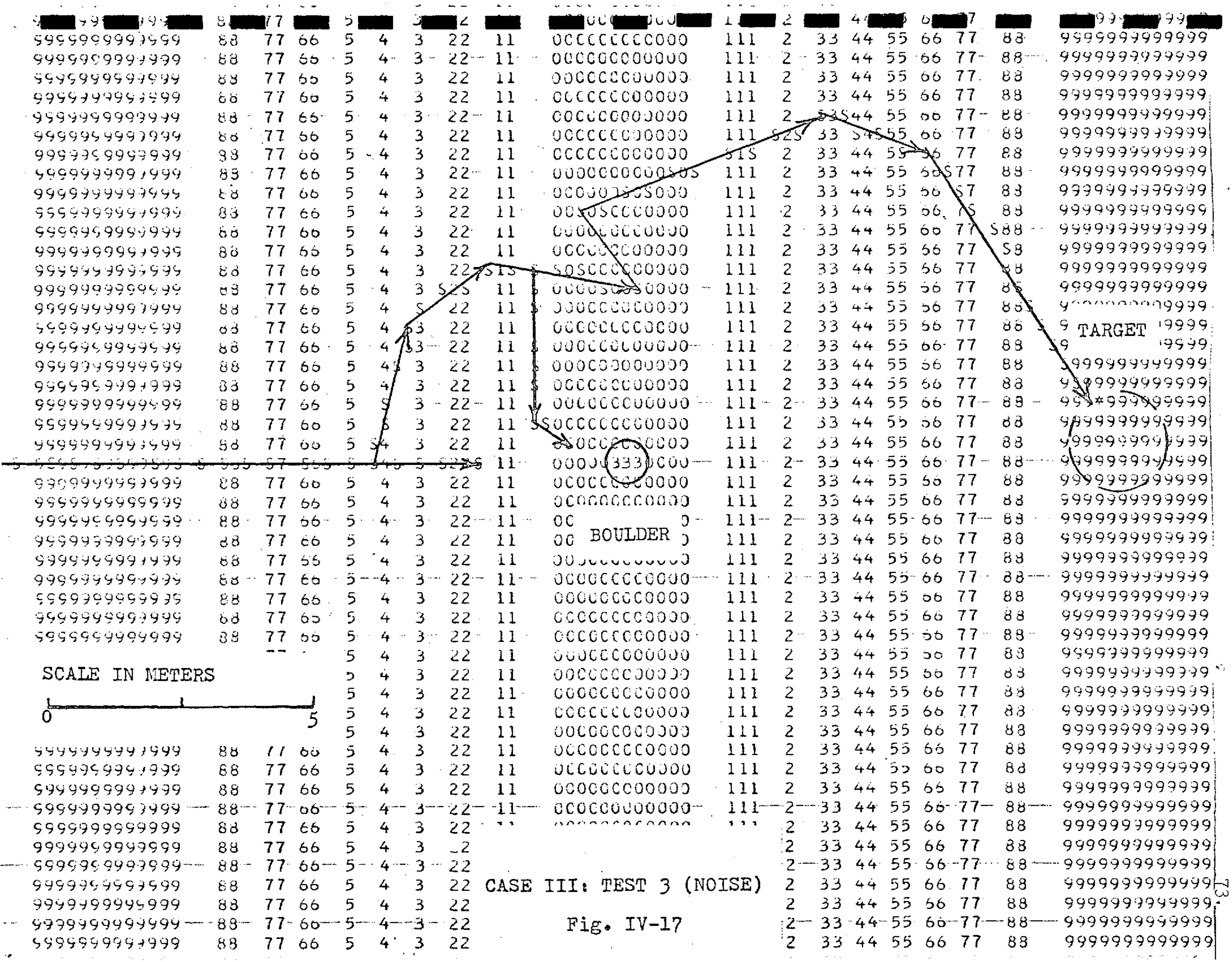
CASE III: TEST 1 (NO NOISE)

Fig. IV-15



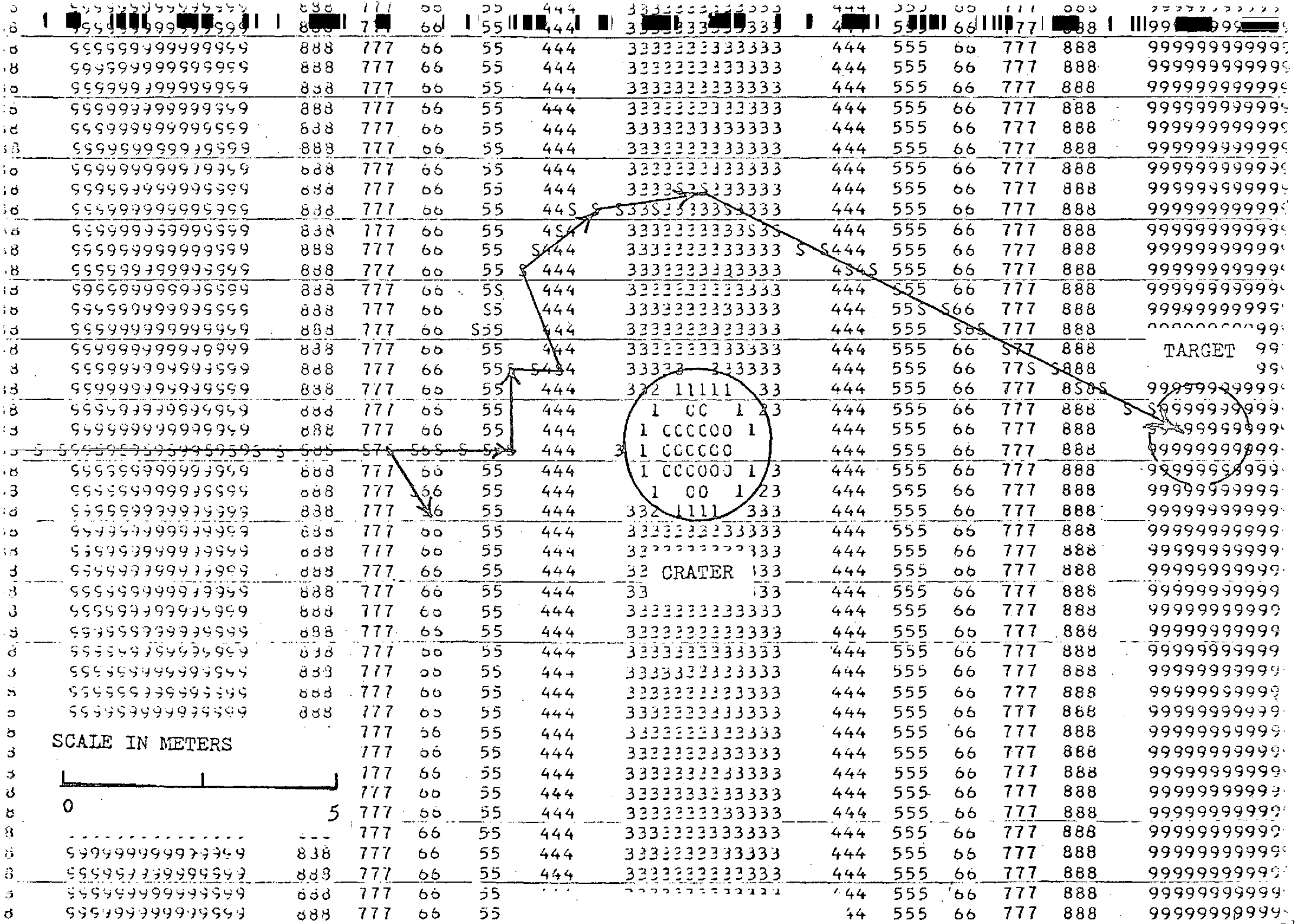
CASE III: TEST 2 (NO NOISE)

Fig. IV-16



CASE III: TEST 3 (NOISE)

Fig. IV-17



CASE III: TEST 4 (NOISE)

Fig. IV-18

4. Case IV: Single Obstacle Encounters on a Rolling Incline

A seven meter high rolling incline test terrain was used to examine the short range system's performance on a hillside. Baseline runs for deterministic and noisy performance produced identical output that indicated the vehicle would climb directly up the incline to target. In subsequent simulations a single boulder or crater was placed near the crest of the hill as shown in Fig. IV-19. The same obstacles used in Case III were employed but a spherically shaped boulder was used instead of the drum type.

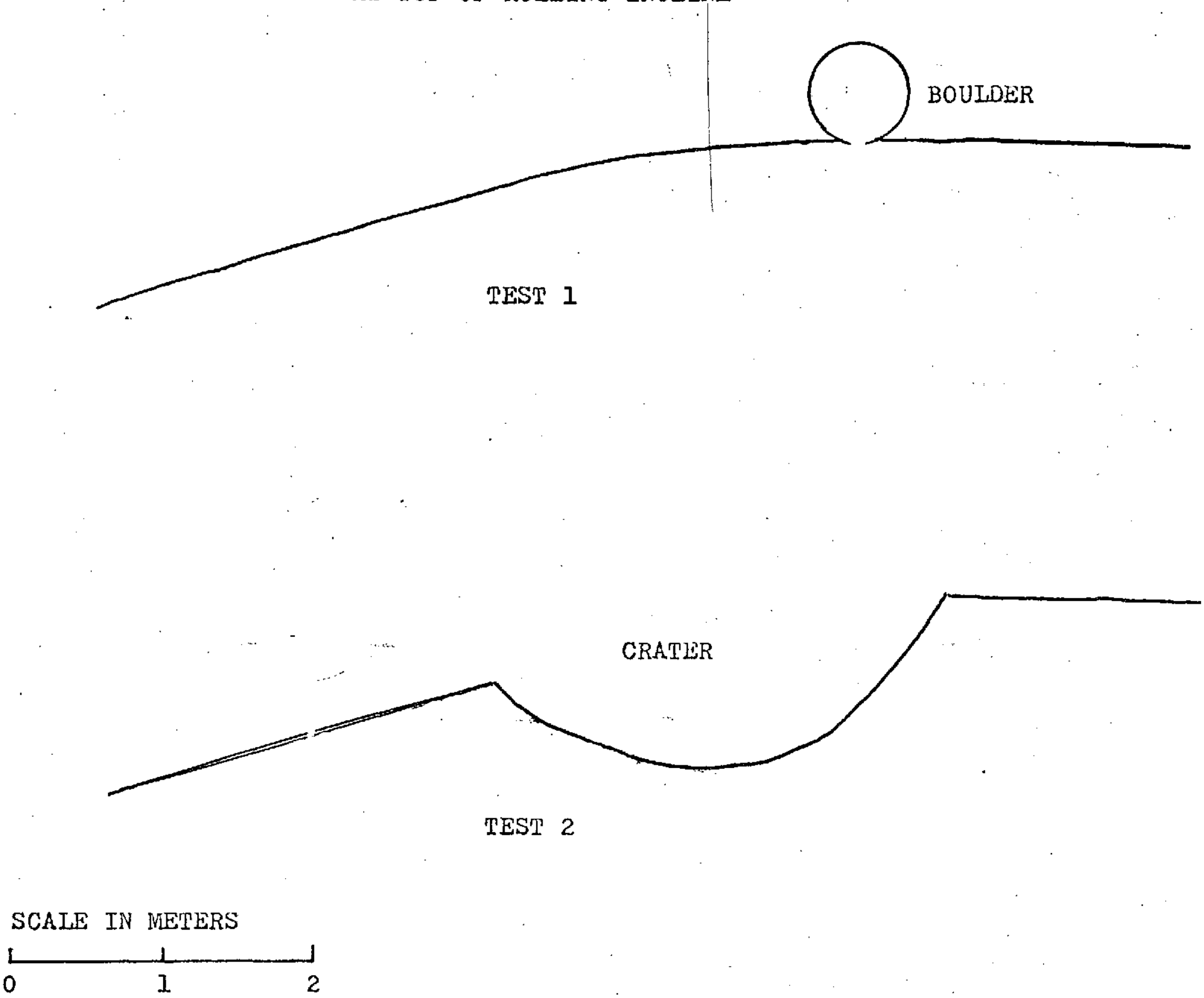
Deterministic encounters were simulated first and in each case the vehicle struck the obstacle at the top of the hill. Figure IV-20 is a reconstruction of the events that resulted in the collision with the boulder. As the vehicle approached the crest of the hill the forward beam was gimballed over the boulder allowing it to come beneath the swinging arm as the vehicle continued to move forward. The shape of the boulder and the attitude of the vehicle then resulted in a failure to detect the boulder through a down beam slope measurement. The vehicle proceeded forward to collide with the bculder.

The events that led to the collisi n with the crater are shown in Fig. IV-21. A combination of the crater's orientation relative to the approaching vehicle and the chance impingement of the down beam just inside the crater's edge fails to result in a slope measurement that exceeds the 25° threshold. The crater goes undetected and the collision occurs.

At this point further simulations on this terrain were discontinued pending changes in the short range system.

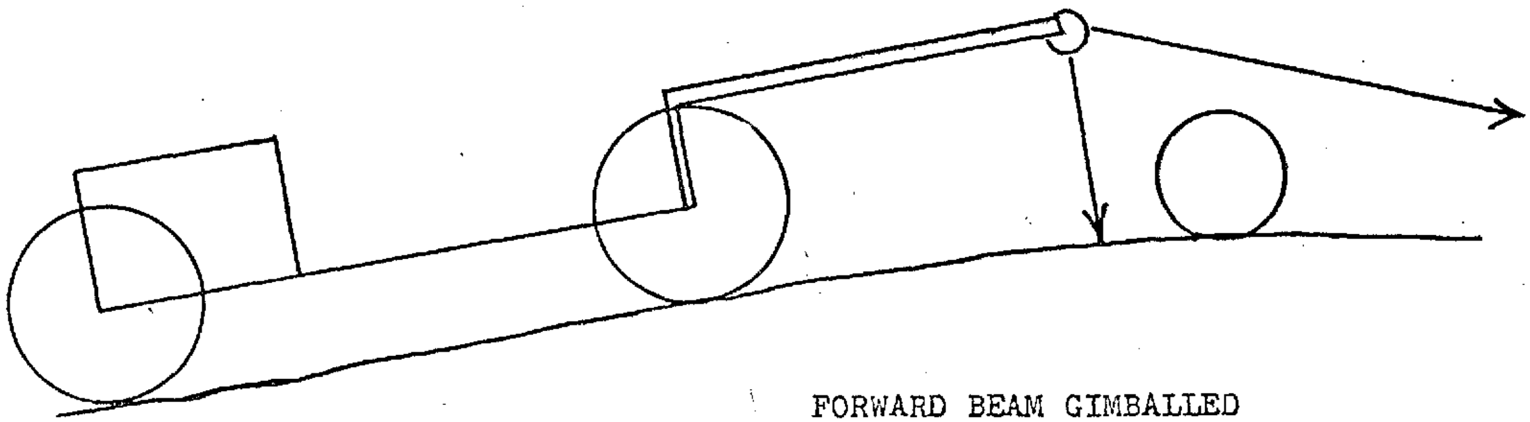
TERRAIN PROFILES

AT TOP OF ROLLING INCLINE

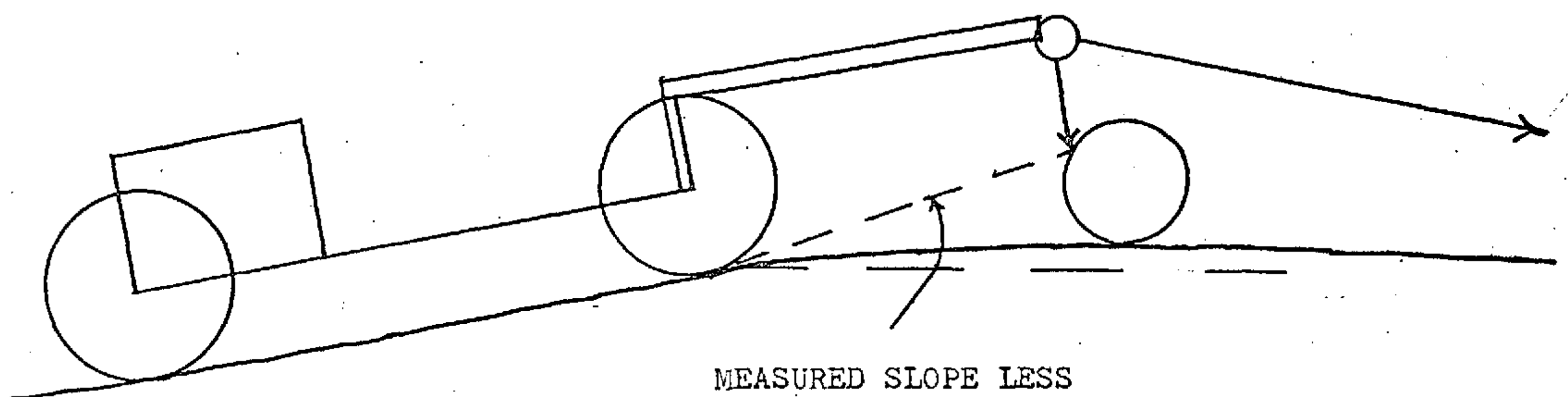


OBSTACLE LOCATIONS FOR CASE IV

Fig. IV-19



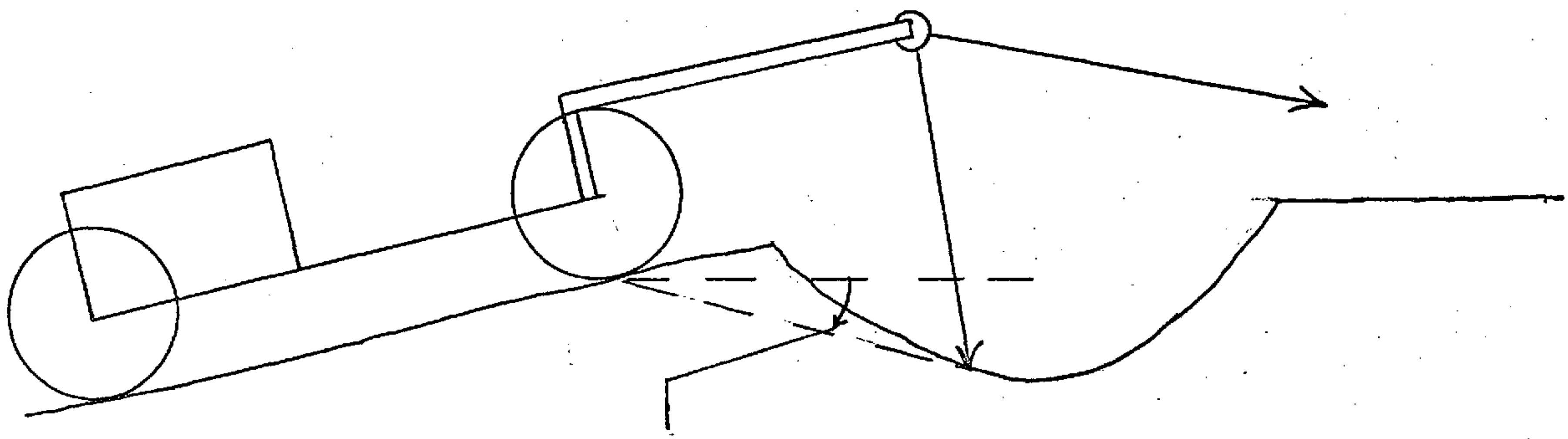
FORWARD BEAM GIMBALLED
OVER THE BOULDER



MEASURED SLOPE LESS
THAN THRESHOLD

CASE IV: BOULDER ENCOUNTER (NO NOISE)

Fig. IV-20



MEASURED SLOPE LESS THAN THRESHOLD
RESULTS IN COLLISION WITH CRATER

CASE IV: CRATER ENCOUNTER (NO NOISE)

Fig. IV-21

5. Case V: Boulder-Crater Field

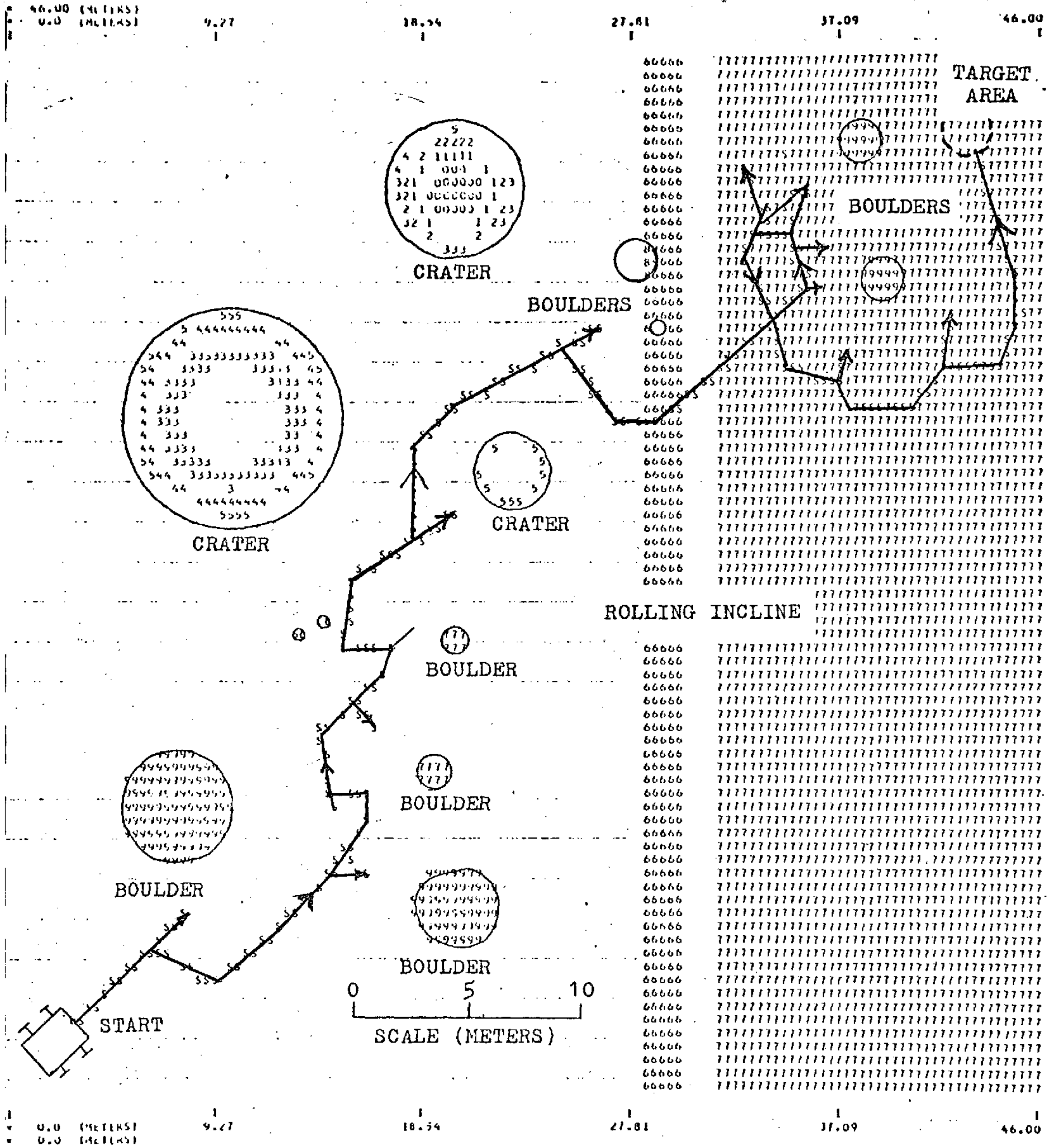
The test terrain shown in Fig. II-7 was used as a final examination of the short range system's ability to avoid boulders and craters on relatively flat base terrain. The vehicle path map for this simulation shown in Fig. IV-22 indicates that the system performed reasonably well and reached target successfully. This performance was awarded a low figure of merit of 0.413 as a result of the vehicle's backing over the two small boulders midway in Fig. IV-22. This occurred as a result of an oversight in not providing a tactile sensor on the rear of the vehicle.

An interesting aspect of the system's behavior was exhibited as the vehicle approached the two boulders near the target position. The vehicle path oscillates between encountering one then the other boulder because this memoryless system repeatedly commits the same mistakes.

D. Conclusions and Recommendations

The results of Cases I, II and V indicate that the memoryless short range system performs reasonably well in the presence of moderate amounts of noise on relatively flat base terrains. However, Cases III and IV show that this performance degrades in the presence of non-zero local slopes and noise. Frequently these effects cause the system to confuse clear terrain for an impassable feature. Simulation output for these cases seems to indicate that improper gimballing due to range and slope measurement noise is the principal cause of this confusion.

All of the simulations indicate that a memory capability and more extensive path selection algorithm would enhance the system's performance. The system should be changed so as to not only estimate the size, type



CASE V: BOULDER-CRATER FIELD (NOISE)

Fig. IV-22

and location of the detected obstacle but to store this information for future reference. In addition, keeping a record of the current average in-path slope would lend itself to estimating the type of terrain that is being traversed. This information could be used to control the vehicle's speed and the sensors' orientation to obtain better performance near the crest of a hill or on a rolling terrain.

To conclude, this analysis indicates that path selection based upon limited range-azimuth information is feasible. Further work in this area should concentrate on examining a system with a memory capability and a more elaborate path selection system control algorithm, giving particular attention to the system's noisy performance on rolling base terrains. The simulation should be expanded to include a scanning operation that would require a finite amount of time and take into account the vehicle's motion.

V. SUMMARY

A. Summary of Progress

Over the past three years a roving-vehicle path selection evaluation system has been developed. The system can realistically simulate and quantitatively evaluate the performance of a wide variety of path selection systems under consideration for a Martian roving vehicle. The computer package includes the capability of simulating random effects due to vehicle bouncing, sensor error, and slope measurement error.

During the past fifteen months a set of standard test terrains and simulation procedures has been developed. In addition two path selection systems have been evaluated to determine the usefullness of the standard testing procedure and to determine the strengths and weaknesses of the proposed systems.

B. Future Work

1. Standard Test Terrains and Procedures

The development of standard test terrains and simulation procedure represents a first attempt at establishing a uniform means for path selection system evaluation using the computer simulation package.

As more information about the actual Martian surface becomes available the standard test terrains should be updated to maintain a high level of realism. However, the general format of beginning with simple obstacle encounter situations and then proceding to progressively more complex terrains should be maintained.

The terrain characterization block of the computer simulation package has the capability of building Gaussian distributions to convey low frequency terrain features. It appears that with the use of Gaussian hills many realistic standard test terrains could be developed. It is suggested that the use of this type of terrain characterization be investigated.

At present the user is free to select any weights desired for use in the calculation of the quantitative performance index. The development of a procedure for establishing these weights, which would take into account the complexity of the terrain being used and the system design, would help to increase the usefullness and reliability of the performance index.

2. Evaluation of a Mid-Range Sensor System

The analysis of the proposed mid-range sensor system has not only demonstrated that the system has some promising features, but has also shown where some of the system weaknesses exist. It is suggested that the recommendations for system improvements, which resulted from the evaluation, be applied to other mid-range sensor systems and that an improved modification of this system be evaluated.

3. Development of a Short Range Sensor System

The development and evaluation of a short range sensor system should be continued. It is suggested that additional efforts be directed at determining the constraints which a short range sensor system places on the vehicle design and performance. It is more important to determine what factors are critical to the successful performance of the system than to actually design a particular sensor scheme.

4. Evaluation of Future Systems

The objective of this research is to evaluate proposed path selection systems and to develop new path selection system concepts. Therefore, in addition to the continued investigation of the subjects discussed in this report, promising new path selection systems will be evaluated.

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2. Marshall, R. R., "The Mars Terrain -- A Description for Motion-Control Evaluation of a Roving Vehicle," Jet Propulsion Laboratory, Pasadena, California.

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